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Economic Geology

and the

Bulletin of the Society of Economic Geologists

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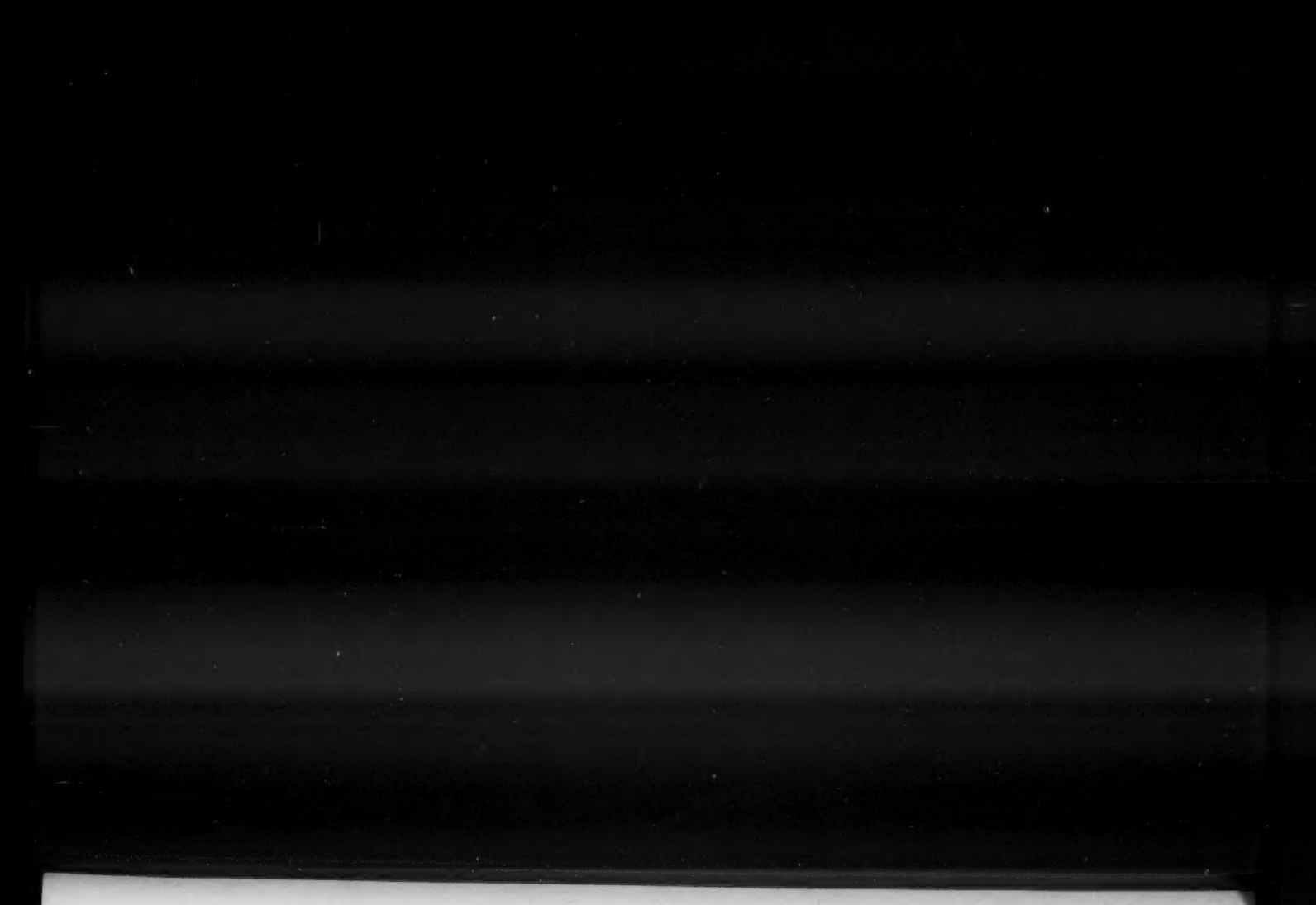

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HYDROTHERMAL ALTERATION IN THE "PORPHYRY COPPER" DEPOSITS.[1]

GEORGE M. SCHWARTZ.

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ABSTRACT.

The hydrothermal alteration, which was accompanied by the introduction of copper sulphides in the disseminated copper deposits, is considerably more complex than is generally recognized.

Detailed microscopic study of selected porphyry specimens from the important deposits in the United States, together with a review of published data, leads to the recognition of four main types of alteration which are designated as follows: 1. Quartz-orthoclase; 2. Quartz-sericite-

[1] Published by permission of the Director, U. S. Geological Survey.

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pyrite; 3. Sericitic and argillic alteration with quartz subordinate; 4. Biotitic alteration.

No district is a simple example of one kind of alteration but each district shows a dominance of one or two of the above types. Most districts show a rather long list of alteration products when studied in detail.

The argillic alteration has been little emphasized in earlier work, but is now known to be very important in several districts of which Morenci is an outstanding example. The clay minerals occur in the sulphide ore and are characteristically earlier than sericite.

The more important clay minerals include hydromuscovite, kaolinite, allophane, halloysite, and beidellite. Less common are potash clay, montmorillonite, and dickite.

Available chemical data indicate that calcium and sodium are generally removed from the rock to a significant degree, and potassium remains constant or increases. Silica is gained in a few deposits but commonly shows minor changes. Quartz, no doubt, is often formed by the freeing of silica during alteration.

The relation of copper content to the various kinds or stages of alteration is indicated in a general way pending detailed studies in all districts. The problem differs depending upon whether the deposits are those where enrichment is important or where they are primary deposits of commercial grade. In enriched deposits the distribution of pyrite with respect to the alteration is of considerable importance. In primary ores the evidence indicates that chalcopyrite was introduced with the sericitic alteration and less commonly with biotite. Pyrite often accompanies sericite but at San Manuel the highly pyritic alteration accompanies a dominantly hydromuscovite alteration, whereas chalcopyrite plus some pyrite occurs with intense sericitic alteration.

INTRODUCTION.

DISSEMINATED copper ores in porphyry and less often in schist form a remarkable series of deposits with many common features. So much emphasis has been placed on these common features that significant differences tend to be overshadowed. In many respects this is especially true of the hydrothermal alteration of the porphyry which was accompanied by disseminated metallization. In some deposits the primary metallization formed ore, in others only protore was formed which was converted to ore in limited areas by supergene enrichment. In most general descriptions [2] the rock alteration is described as mainly the formation of sericite and quartz with some chlorite. As in most generalizations this is a somewhat over-simplified statement of the situation. It has long been known that there was considerable variation in the alteration but Gilluly's [3] work on Ajo served to emphasize that the New Cornelia ore body was unique in the intensity of orthoclasization and the relatively subordinate role played by other processes of alteration.

Development of the Castle Dome [4] deposit during the war revealed an

[2] Lindgren, W., Mineral Deposits: McGraw-Hill, New York, p. 628, 1933.
Emmons, W. H., Relations of the Disseminated Copper Ores in Porphyry to Igneous Intrusives: A. I. M. E., Tech. Paper 1638—I, p. 4, 1927.
Bateman, A. M., Economic Mineral Deposits: Wiley and Sons, New York, p. 386, 1942.

[3] Gilluly, James, Geology and Ore Deposits of the Ajo Quadrangle, Arizona: Univ. of Ariz., Ariz. Bur. of Mines Bull. 141, 1937.

[4] Peterson, N. P., Gilbert, C. M., and Quick, G. L., Hydrothermal alteration in the Castle Dome Deposit, Arizona: ECON. GEOLOGY 41: 820–840, 1946.

example of hydrothermal alteration in which argillaceous minerals were developed earlier than sericite, which was formed along quartz-pyrite veins. This served to call attention to the importance of argillic alteration in disseminated deposits as had been done earlier by Lovering for veins.[5]

Somewhat later, drilling revealed a disseminated copper deposit in a highly altered area just south of Tiger, Arizona on the San Manuel claims.[6] Study of this alteration by the writer has shown an unusual series of four kinds of alteration. Comparison with other districts indicates a somewhat more complex alteration problem at San Manuel than in the other disseminated copper deposits.

In attempting to work out the relations in the San Manuel area as a guide to exploration beneath a heavy cover of conglomerate the whole problem of types of hydrothermal alteration in the disseminated copper deposits in porphyry was reviewed for comparative purposes. This in turn led to a critical study of the type of alteration and the relation of copper content to the alteration. Visits to the deposits permitted direct comparison, and study of suites of thin-sections followed.

Preliminary data now available permits separating the so-called "copper porphyry" deposits into several groups based on the mineralogy of the hydrothermally altered porphyries. This study is merely a reconnaissance of the problem which will require much more detailed work.

Acknowledgements.—In the course of a broad study such as forms the basis of this paper, one inevitably becomes indebted to a great number of individuals and also mining companies controlling the properties. Without their liberal assistance little could have been accomplished. In addition, much assistance has been rendered by others in the course of laboratory work. Thanks in particular is due to T. S. Lovering and Bronson Stringham for invaluable assistance in the microscopic determination of the many alteration products; also to John W. Gruner for a considerable number of X-ray patterns used as a check against microscopic determinations. The laboratory facilities of the University of Minnesota were used throughout and research funds made available by the Graduate School made possible aid in preparation of the manuscript.

The data on Castle Dome were furnished by Nels Peterson and C. Gilbert, that for Bagdad by C. A. Anderson, all of the United States Geological Survey. S. G. Lasky, also of the Survey gave invaluable aid in the Chino area. G. S. Espenshade and Ralph Cannon Jr. read the manuscript and made many suggestions. The literature on all deposits was used freely and appropriate footnotes are acknowledgement of this fact in each case. Finally the writer is deeply indebted to the United States Geological Survey whose support made the work possible.

Types or kinds of alteration.—In most disseminated copper deposits there is a rather complex series of alteration products that vary with the mineral

[5] Lovering, T. S., The origin of the tungsten ores of Boulder County, Colorado: ECON. GEOLOGY 36: 229–279, 1941.

[6] Schwartz, G. M., Geology of the San Manuel area, Pinal County, Arizona: U. S. Geol. Survey, Strategic Minerals Investigations, Prelim. Maps 3–180, April 1945.

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composition of the original rock, the intensity of alteration, and the nature of the hydrothermal solutions. In attempting to group the deposits, one is confronted with the danger of over-simplification on the one hand and too complicated a classification on the other hand. In the following classification and discussion the writer has intended to keep the classification simple.

Broadly considered there are at least four main types of alteration in the copper porphyries with considerable overlap and with minor variations. These types refer to the ore and not to marginal zones. The more or less distinct types, with examples of districts in which these are important, are as follows:

1. Quartz-orthoclase. Alteration to and/or introduction of quartz and orthoclase. Ajo, Ely, Bagdad, Bingham (in part).

2. Quartz-sericite-pyrite. Inspiration-Miami, Ray, Sacramento Hill, Castle Dome (in part), Bingham (in part).

3. Sericitic and argillic alteration. Quartz subordinate. Morenci, Chino, Castle Dome (in part), San Manuel.

4. Biotitic alteration. Bingham and Ely, Nevada. Some of this facies is also shown at Bagdad and San Manuel.

It should be emphasized that no district is a simple example of one kind of alteration. The more the alteration of each district is studied in detail, particularly in thin-section, the more it is realized that most districts show several kinds of alteration, though perhaps one kind may overshadow the others as at Ajo. Each deposit can thus be best classified as having one or more dominant types of alteration. Bingham, for example, has a large amount of ore in which quartz-sericite and quartz-orthoclase are dominant, and also a large mass in which biotitic alteration is very definitely dominant. In most deposits there are also alteration zones or facies that are marginal to the ore zone and were formed by the same hydrothermal processes as the ore zone.

A matter of great importance in connection with the problem of hydrothermal alteration is the increasing amount of primary ore in present production of several disseminated deposits. In the Utah Copper Mine at Bingham, the New Cornelia Mine at Ajo, Arizona, and the Ely district, Nevada, primary ore is now much more important than ore that has been subject to supergene enrichment. It is therefore possible in these deposits to study ores that have been formed during hydrothermal alteration and have not subsequently undergone supergene alteration of any sort. The clay minerals described below would be assigned by many to an origin by weathering if this process has been active. It certainly would be difficult in the present state of knowledge to attempt, in the same specimen, to separate clay minerals of hypogene origin from those of supergene origin. Therefore, in the present investigation, study was concentrated insofar as possible on specimens free from weathering or secondary enrichment.

SUMMARY OF HYDROTHERMAL ALTERATIONS IN THE "PORPHYRY COPPER" DEPOSITS.

Ajo, Arizona.—The New Cornelia ore body at Ajo, Arizona, is the best example known among the disseminated copper deposits of the formation of quartz and orthoclase on a large scale, with the result that Gilluly [7] refers to it as almost pegmatitic along the two main zones of intense alteration.

The unaltered rock is a quartz monzonite. The alteration which accompanies the copper mineralization affects a larger area than that occupied by the copper deposit and is complex in detail. Gilluly believes that in an early alteration, probably deuteric, orthoclase was introduced into the groundmass where it indents quartz and feldspar phenocrysts. Although found outside of the ore body, this alteration is most pronounced in the pit area.

Following consolidation, the monzonite was extensively fractured in the area of the New Cornelia ore body and hydrothermal solutions permeated the mass. The earliest stage resulted in the formation of a coarse orthoclase-quartz-biotite rock essentially pegmatitic in nature. This material was largely limited to main fracture zones. In 1946 the amount visible in the pit was small. Throughout much of the area of the pit, fine-grain pink orthoclase has extensively replaced the groundmass of the monzonite. Quartz commonly accompanied the feldspar and locally silicified the rock to a notable degree. Some magnetite was formed closely following the formation of the pegmatite and is localized near it.

Following the main deposition of orthoclase was a period of complex alteration very nearly like that of many other "porphyry copper" deposits. Pyrite, chalcopyrite, and bornite are the common primary sulphides. Tetrahedrite, molybdentie, and sphalerite occur in small amounts. Coincident with the deposition of the sulphides hydrothermal solutions caused plagioclase to alter to albite and sericitic aggregates, and the ferromagnesian minerals to chlorite, epidote and minor amounts of other minerals. This part of the alteration is much like that of the more common type of porphyry copper alteration except for the presence of albite.

According to Gilluly albite formed not by introduction of soda but rather as a result of destruction of the anorthite molecule. Considerable recrystallization or rearrangement must have taken place, for the volume of albite is necessarily much less than that of the original plagioclase. Quartz is abundant in the larger veinlets, in some to the practical exclusion of orthoclase, and chalcopyrite and bornite are more abundant in the veins than in the altered host rock.

Analyses listed by Gilluly show less CaO and more K_2O in the ore as compared with fresh porphyry. SiO_2, Al_2O_3, Na_2O, MgO, and Fe show little change. Chemically the changes are analogous to those of some of the porphyry ores in other districts, but at Ajo introduced orthoclase is dominant instead of sericite.

[7] Gilluly, James, Geology and ore deposits of the Ajo Quadrangle, Arizona: Arizona Bur. Mines, Geol. Ser. No. 9, Bull. 141, 1937. The mineralization of the Ajo copper district, Arizona: ECON. GEOLOGY 37: 247–309, 1942.

Bagdad, Arizona.—At Bagdad [8] a somewhat porphyritic quartz monzonite has been extensively fractured and the larger fractures or fissures filled with sulphides; most of the ore occurs in smaller fractures along which sulphides are disseminated. The mineralization, or at least the copper sulphide, permeates the rock only to a limited degree. The rock is less altered than most copper porphyry deposits and the ore is closely related to fractures. Butler and Wilson state that much of the feldspar is clouded with sericite and the biotite is in part altered to chlorite or bleached to muscovite. In a more recent, comprehensive study of the district, Anderson [9] has found that the entire stock in which the copper occurs is altered but a smaller stock to the southwest is practically unaltered, thus furnishing a useful comparison.

As described by Anderson, the unaltered quartz monzonite has a seriate to porphyritic texture with plagioclase ranging from calcic oligoclase to andesine and usually exceeding the orthoclase which occures in the matrix. Biotite, with a book habit, is the ferromagnesian constituent.

In the mineralized rock the texture is more granular in comparison to the fresh quartz monzonite, plagioclase is more sodic, orthoclase is equal to, or in excess of, plagioclase, and quartz is coarser grained and more abundant. Relics of book biotite remain but much of the mica is pale and leafy in habit. The early stage of alteration evidently resulted in albitization of plagioclase and also some replacement by orthoclase and quartz. Chlorite and sericite formed locally. Quartz-orthoclase veinlets follow some of the fractures and often contain apatite. Pyrite, chalcopyrite, molybdenite and less commonly other minerals accompany the quartz-orthoclase mineralization. Pyrite and chalcopyrite occur sparsely disseminated in the rock but always with introduced quartz and orthoclase.

In the outcrops around the mineralized area there are irregular masses of white granular rock which contain clear orthoclase, albite to sodic oligoclase, with appreciable sericite in veinlets and clusters. Biotite is usually absent but of leafy habit where present. This seems to represent quartz monzonite altered under conditions more favorable to sericite. Elsewhere a more resistant rock appears to represent quartz monzonite largely replaced by an interlocking aggregate of quartz, orthoclase and coarse sericite flakes.

In general the alteration at Bagdad seems rather mild as compared with other porphyry copper districts. It has analogies with facies of alteration known in other districts and perhaps may be said to offer a moderate development of facies or types known at Bingham and at Ely. The quartz-orthoclase alteration and replacement may be compared with Ajo but at Bagdad they are so much less intense that the comparison is, perhap, misleading. As described by Anderson, it is more like the quartz-orthoclase alteration at Bingham and Ely.

The formation of light-brown to green mica is observed in various stages at Ely, Bingham, and San Manuel. The occurrence at Bagdad is no doubt an incipient stage of this type of alteration.

[8] Butler, B. S., and Wilson, E. D., Bagdad Mine, Eureka District: Ariz. Bur. Mines, Geol. Survey 12, Bull. 145, pp. 98–103, 1938.

[9] Anderson, C. A., Personal communication.

Bingham, Utah.—The hydrothermal alteration of the porphyry in the Bingham district [10] was studied in detail in the early days of mining, but very little regarding the deposits, and almost nothing on hydrothermal alteration, have been published in the last 25 years. During that time much of the mining has passed into the zone of primary mineralization so that it is now possible to study material free from weathering and supergene enrichment.

The deposit of the Utah Copper Mine occupies a considerable portion of the Bingham stock and the ore body represents very extensive hydrothermal alteration of the monzonite porphyry. However, in some of the outlying portions of the stock and in the Last Chance stock, it is possible to examine rock that has largely escaped alteration. The Niagara tunnel of the United States Smelting, Refining and Mining Company furnishes access to unaltered porphyry of both stocks.

The problem of rock alteration in the Utah Copper Mine is complicated by the fact that there are two distinct kinds of hydrothermal alteration resulting in the "Dark" and "Light" porphyry as designated by Butler.[11] According to Boutwell [12] the facies are in a general way divided by a fracture zone which trends N. 45° E. and dips 45° NW., with the lower part dark and the upper part light. The better-grade ore is associated with the maximum of bleaching and silicification. This division seems to be less evident as the pit deepens and the dividing line is difficult to see. It appeared to the writer that on the lower levels "dark" and "light" facies are often mixed. The relations of the two are referred to below.

The fresh porphyry of the Bingham stock from the Niagara tunnel is a quartz monzonite porphyry of medium-gray color with augite, hornblende and biotite as ferromagnesian minerals. Feldspar phenocrysts are inconspicuous and quartz appears in the medium-grained groundmass with abundant orthoclase. Detailed descriptions of the porphyry can be found in the reports cited above. Facies more porphyritic than that of the Bingham stock appear elsewhere in the district.

In the Utah Copper Mine the porphyry contains no hornblende or augite and varies in the amount of biotite. The darkest rock contains biotite phenocrysts that are comparatively unaltered; others have recrystallized to aggregates of a paler-brown color in thin-section, still others are green but highly birefringent and some have altered to chlorite. This mica separated out and checked by X-ray gives a biotite pattern. Judging from its appearance in thin-section, some of the pale mica may be hydrobiotite or analogous type of alteration product. There is unquestionably much hydrothermal biotite in the dark porphyry (Fig. 11); some is probably an alteration of hornblende or augite and some replaces primary biotite. The feldspar in this material is considerably altered to sericite, hydromuscovite, kaolinite, and

[10] Boutwell, J. M., Economic geology of the Bingham mining district, Utah: U. S. Geol. Survey, Prof. Paper 38, 1905.
Butler, B. S., and others, Ore deposits of Utah: U. S. Geol. Survey, Prof. Paper 111, 1920.
Beeson, J. J., The disseminated copper ores of Bingham, Utah: Trans. A. I. M. E. 54; 356–401, 1917.

[11] Op. cit., p. 351.

[12] Boutwell, J. M., Copper deposits at Bingham, Utah: Copper Resources of the World, vol. I, p. 353, 1935.

allophane. Sericite is relatively scarce, and the argillic products are abundant. Various specimens of the dark facies contain less biotite than the specimen described above but are otherwise similar. Magnetite, apatite and sphene are common accessory minerals. Sericite is not abundant in the biotite rock. In one specimen a mineral tentatively identified as beidellite occurs abundantly with kaolinite. Pyrite and chalcopyrite often occur in biotite. Butler noted that with more intense alteration the biotite became more evenly distributed.

The light-colored facies is a more obviously altered rock. Biotite originally present mainly as phenocrysts is largely altered to sericite or muscovite with the appropriate bleaching. The groundmass is a fine-grained aggregate of quartz and orthoclase which seems to scallop the original plagioclase crystals. Much of this groundmass is probably replacement and perhaps, in part, recrystallization of the original coarser groundmass. Plagioclase is extensively altered to sericite but orthoclase is usually much less sericitized.

In the very light gray and rather soft rock, the ferromagnesian minerals have been completely destroyed, although areas that were originally biotite are marked by clusters of rutile. Sericite is abundant and is associated with hydromuscovite, kaolinite, and allophane.

In general, the light-colored facies is a rather intensely altered rock with much introduced quartz at places. The impression gained from the microscopic study is that the biotitic rock is a less-altered phase of the original porphyry, characterized by the introduction of considerable biotite and some argillic alteration. In general, there is doubt that the light rock passed through the biotite stage; instead, original biotite, augite and hornblende were largely destroyed, plagioclase was sericitized, and much quartz often accompanied by orthoclase was introduced. Magnetite is lacking in most thin-sections. Readily visible molybdenite is commonly associated with the vein quartz; usually orthoclase is lacking in this late quartz. Beeson [13] considered the silicification and sericitization along parting zones to represent a late hydrothermal stage of mineralization.

The chemical changes in alteration of the Bingham porphyry are indicated by analyses in Professional Paper 111. The fresh porphyry is from the Last Chance stock and analyses of "dark porphyry" and "light porphyry" are given for comparison. The chemical changes are naturally different in the two facies.

The dark biotitic altered rock as compared with fresh rock shows a decided loss of lime and ferric iron, and a significant loss of soda. Other constituents have relatively small gains with water, sulphur, and ferrous iron showing the more important increase. The loss of lime is the outstanding feature of this alteration.

The light rock represents a more intense alteration and therefore has more pronounced changes. Lime, alumina, ferric and ferrous iron, magnesia, and soda show a pronounced decrease and potash alone among the normal rock constituents shows an important increase.

[13] Beeson, J. J., The disseminated copper ores of Bingham Canyon, Utah: Trans. A. I. M. E. 54: 356–401, 1917.

Recalculated mineral compositions also show the distinction. In the dark rock quartz, biotite and muscovite-paragonite molecules show large increases and orthoclase, albite, anorthite, augite and magnetite show a relatively large decrease. In the light rock quartz, orthoclase, muscovite-paragonite show

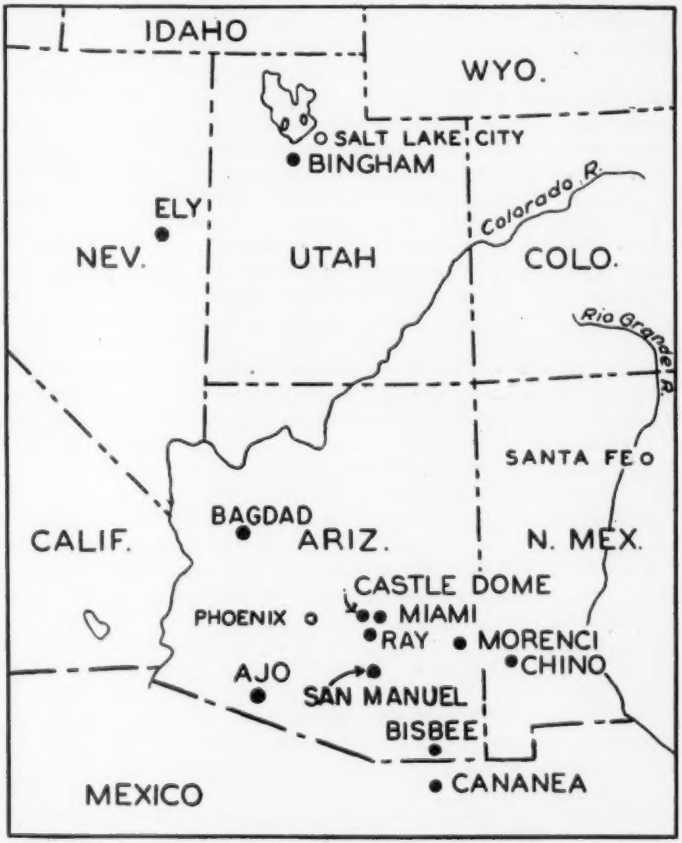

FIG. 1. Index map showing location of deposits discussed.

large gains and albite, anorthite, augite and magnetite show large losses. The distinction between calculated mineral composition of the two altered rocks is largely a complementary relation of biotite and orthoclase.

Microscopic study of a suite of specimens suggests that variations in the gains and losses as stated above would be brought out by a series of analyses of both light and dark varieties. Single analyses cannot be expected to bring

out all of the relations. Microscopically biotite and sericite often seem to be complementary.

In summary, it may be said that the dark facies at Bingham is characterized by biotitization accompanied by considerable alteration of feldspar to hydromuscovite, kaolinite and allophane. Most specimens show some alteration of biotite to green mica (hydrobiotite) and in some specimens, to chlorite. Sericite is distinctly subordinate in this facies.

The light facies is intensely altered. Sericite is abundant. Primary biotite crystals have altered to colorless mica (sericite) and plagioclase is often completely altered to sericite. The groundmass is usually a fine-grained quartz-orthoclase mosaic which has probably formed by recrystallization of primary quartz-orthoclase and by introdction. Hydromuscovite often accompanies sericite. Argillic products are decidedly subordinate but include allophane, beidellite and kaolinite.

Castle Dome deposit, Arizona.—The Castle Dome copper deposit which is about 7 miles west of Miami, Arizona, came into production during the war and furnishes a new example of disseminated copper ore in porphyry.

The ore is found entirely within an area of intense alteration of quartz monzonite [14] and is a result of primary metallization plus secondary sulphide enrichment. The hydrothermal alteration is of unusual interest because it furnishes such a clear-cut example of intense argillic alteration followed by equally intense sericitization along more or less well-defined quartz-pyrite veins and stringers. Chalcopyrite is associated with the veins and occurs both within the veins and disseminated in the wallrock. The ore lies entirely within the area of greatest alteration.

Peterson and his associates recognize three phases of alteration: propylitic, argillic, and quartz-sericitic. The marginal phase is a propylitic alteration of biotite and plagioclase to sericite, epidote, clinozoisite, chlorite, calcite and leucoxene. In general, quartz, orthoclase and apatite are not affected. Sphene is partly or completely converted to leucoxene, ilmentite shows leucoxene rims, and the titanium in biotite is recrystallized to minute rutile grains and leucoxene. The propylitic alteration extends beyond the area of sulphide mineralization.

The stronger argillic alteration has bleached the rock somewhat; the plagioclase appears chalky and tends to slake when exposed. It is largely altered to clay minerals principally hydrous mica and a montmorillonite-type clay resembling beidellite. Locally, orthoclase and biotite are attacked but some fresh biotite remains. Some of the biotite is altered to buff-colored pseudomorphs, mainly kaolinite, or is recrystallized to aggregates of small grains. Sphene and ilmenite are altered to leucoxene and apatite is largely destroyed. This argillic phase of alteration is most intense in the mine area and diminishes toward the north and south.

The quartz-sericite alteration is localized along quartz-pyrite veins and the wallrock for as much as an inch away from the vein may be almost entirely

[14] Peterson, N. P., Gilbert, C. M., and Quick, G. L., Hydrothermal alteration in the Castle Dome copper deposit (Abstract): Bull. Geol. Soc. America, vol. 56, p. 1190, 1945. Also Econ. Geology 41: 820–840, 1946.

replaced by sericite and, to a less extent, by quartz and a little pyrite and adularia. Plagioclase has been most susceptible to sericitization. Quartz is somewhat attacked and orthoclase may be altered close to the veins. Aggregates of rutile represent original titanium-bearing minerals such as sphene and biotite. Small amounts of adularia occur in the quartz-sericite alteration, but seem to be lacking in the quartz-pyrite veins.

Primary chalcopyrite occurs in the quartz-pyrite veins and disseminated in the adjacent wallrock. The quartz-sericite alteration is superimposed on the argillic and also the propylitic facies and does not constitute a well-defined zone, but a central area of intense pyritization and quartz-sericite is recognized.

Chemically the clay and clay-sericite phases of alteration show moderate loss of silica but the quartz-sericite phase shows an increase. Alumina shows decrease in both the clay and quartz-sericite phases. Magnesia is virtually constant in the clay phase but shows a loss in the sericite phase. Lime and soda show a pronounced decrease in both phases. Potash shows an increase in the clay and clay-sericite phases and a decrease in the quartz-sericite phase. Introduction of both iron and sulphur is important in the quartz-sericite phase. Iron shows a decided decrease in the clay and clay-sericite phases of alteration.

Miami district, Arizona.—The Inspiration and Miami ore bodies are mainly in Pinal schist, but offshoots of the Schultze granite, usually a porphyritic facies, occur in and near the ore bodies, and a porphyry sheet largely overlies the Inspiration ore body.[15]

The porphyry in and near the Inspiration ore body is highly altered especially by silicification. The silicification is greatest near the porphyry-schist contact and fades out away from the contact except along fault zones. Accompanying silicification is more or less sericitization and introduction of pyrite. Fractures have been filled with quartz which also replaced the adjacent porphyry to some extent.

On the south side of the Inspiration mine porphyry is mineralized near the Sulphide fault. A thin-section of a typical specimen shows alteration to sericite and kaolinite with orthoclase clouded by allophane. The groundmass is a fine-grained aggregate of quartz and orthoclase (Fig. 13) which is so much finer grained than in any of the fresh rock that is seems plausible to view the quartz-orthoclase as a result of recrystallization and introduction during alteration. At places veinlets of coarser orthoclase and also a small veinlet of sericite and chlorite cut the mosaic.

In the Miami Mine dikes cut the ore body and are exposed in the haulage levels beneath. A thin-section of a dike from the 720 foot level shows quartz veinlets with a minor amount of orthoclase. Plagioclase phenocrysts have been altered to a mat of sericite, with less hydromuscovite, kaolinite and halloysite. Bornite and chalcocite replace chalcopyrite. The groundmass is a fine-grained quartz-orthoclase mosaic.

A specimen from the 1,000-foot level shows somewhat similar alteration, but biotite seems largely unattacked. Plagioclase feldspar phenocrysts are

[15] Ransome, F. L., The copper deposits of Ray and Miami, Arizona: U. S. Geol. Survey, Prof. Paper 115, 1919.

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now pseudomorphs of alteration products in which nontronite is abundant, with less sericite, hydromuscovite and kaolinite. Kaolinite is earlier than the nontronite and sericite. Clusters of rutile are characteristic but their source is not evident. Pyrite and chalcopyrite are sparse. The presence of kaolinite, halloysite, and nontronite in sulphide rocks beneath the ore bodies leaves no doubt as to the hydrothermal origin of part of the argillic minerals in the Miami district. They are not conspicuous, however.

The thin-sections of the altered porphyry from the Inspiration and Miami area show a very fine grained quartz-orthoclase mosaic which is much finer grained than any groundmass seen by the writer in the unaltered rocks of the area, although Ransome [16] described a marginal facies as having an extremely fine grained groundmass. The intrusives in the area of the ore bodies are believed to be offshoots of the Schultze granite as the ores lie along the northern contact of the intrusive. A hydrothermal origin of the fine-grained quartz-orthoclase (Fig. 13) has been suggested by John A. Legge, Jr.[17] He studied the ores of the Miami mine and suggested three stages of alteration of the intrusives, that is, orthoclasization, sericitization, and kaolinization. The last he assigned to supergene alteration. The porphyry was found altered to a fine-grained rock except for original quartz phenocrysts. The borders of these quartz crystals are attacked by orthoclase. Feldspars are altered to sericite, and silicification accompanied both orthoclase and sericite. Legge found little of the fine-grained quartz-orthoclase in the ore-bearing schist. In the light of the occurrence of this quartz-orthoclase mosaic in other porphyry ores, the writer suggests that Legge's classification of the material in the Miami mine as hydrothermal is correct, but much of the quartz-orthoclase is a result of recrystallization rather than introduction. Potash probably increased somewhat because plagioclase shows alteration to sericite.

The silicification of the schist and porphyry, particularly by innumerable quartz veinlets, has been emphasized. Much of this quartz is apparently a rearrangement of silica during alteration. Reference to the series of analyses quoted by Ransome [18] fails to indicate much increase in silica. He gives four analyses of schist which average 66.73 per cent SiO_2, whereas 5 of protore average 69.80 and four of ore average 67.88 per cent at best less than a five per cent increase. Ransome, however, emphasizes the quartz veinlets in these words "The features that especially distinguish it (protore) are the innumerable veinlets, carrying quartz and pyrite, that traverse the rock in all directions. . . ."

A change of five per cent in silica seems small compared with the total content of over 65 per cent, but looked at in another way it becomes more significant. An increase of silica of five per cent means a corresponding decrease of other constituents, mainly the basic elements. A loss of five per cent of these elements would mean a freeing of a corresponding amount of silica; thus the quartz in the rock may well increase 10 per cent or more.

The principal losses of the bases in the schist protore as compared with

[16] Op. cit., p. 61.
[17] Master's Thesis, University of Arizona.
[18] Op. cit., p. 159.

normal schist at Ray and Miami are in soda and lime; the same is true for most of the prophyry ores. These losses mainly represent the destruction of plagioclase feldspar. One gram of sodium lost from plagioclase releases 4.4 grams of silica unless it is tied up in hydrous aluminum silicates. A loss of one gram of calcium releases 2.14 grams of silica.

In summary, it may be said that hydrothermal alteration of porphyry in and near the ore bodies of the Maimi district is characterized by sericite and quartz together with slight formation of orthoclase. A group of clay minerals complicates the alteration and furnishes analogies with the alteration of other copper porphyries particularly the Castle Dome deposit where the various facies are more highly developed.

Ray, Arizona.—The disseminated copper ores of the Ray district have been described in detail by Ransome.[19] The writer confined his attention largely to the small but well-altered porphyry bodies in and near the ore-bearing area. Ransome reports that, in general, the porphyry was a better host rock than the more abundant Pinal schist. He also recognized that kaolinitic alteration at Ray was, at least in part, earlier than sericite, a situation now found to be widespread. His statement[20] is as follows: . . ."where, as in these rocks and in the protore, kaolinite occurs in association with sericite, it is the older mineral and has been metasomatically attacked by the sericite."

The principal porphyry within the ore area is a stocklike mass near the eastern end of the ore body. This porphyry is extensively altered and cut by quartz veinlets. The original plagioclase phenocrysts are characteristically altered to pseudomorphs which are a complex of sericite, hydromuscovite, kaolinite and allophane. In a specimen from the railroad cut near No. 3 shaft, sericite is subordinate and halloysite is abundant in addition to hydromuscovite and kaolinite. A specimen from a dike within the mineralized area and above the ore body shows extreme sericitization. Quartz veins are fairly abundant and a small amount of allophane and kaolinite also occurs.

There are many small dikes of prophyry within the ore and they are about of the same copper grade as the adjacent schist. This porphyry dike ore is bleached and well impregnated with chalcocite which has replaced the primary pyrite. In general, there is much less evidence of silicification than in the Inspiration and Miami ore bodies.

Beyond the limits of the ore bodies the porphyry is less severely altered south of the village of Sonora. Slightly weathered porphyry shows incipient hydrothermal alteration, but primary biotite and hornblende remain as evidence that the effect is much less severe than in and above the ore bodies where the ferromagnesian minerals have been destroyed. Plagioclase has fairly numerous shreds of sericite, some kaolinite, hydromuscovite and allophane. Ferromagnesian minerals are partly altered to chlorite and the groundmass consists of a fresh-appearing mosaic of quartz-orthoclase.

Ransome relates the sericite to the metallization of the porphyry because sericite is often closely related or actually found in quartz veinlets containing

[19] Ransome, F. L., The copper deposits of Ray and Miami, Arizona: U. S. Geol. Survey, Prof. Paper 115, 1919. U. S. Geol. Survey Geol. Atlas, Ray folio (no. 217), 1923.

[20] Op. cit., p. 161, also figure 24.

pyrite, chalcopyrite and molybdenite. Chlorite is rare in the ore but as noted above is found in the marginal alteration. In this connection a significant exposure was noted in the Teapot Mountain porphyry near the highway about a mile northwest of Ray. The Teapot Mountain intrusive is a quartz monzonite porphyry with prominent orthoclase phenocrysts as much as 3 centimeters in length associated with smaller grains of plagioclase, orthoclase, quartz and biotite which are, in turn, embedded in a very fine-grained quartz-orthoclase groundmass. In a dry wash north of the highway to Superior, shear zones cut the porphyry and on the dump of a small shaft and also the north wall of the wash orthoclase phenocrysts were observed to have been converted to dark-gray pseudomorphs. In thin-section these pseudomorphs are found to consist of calcite, chlorite and some residual feldspar. Chlorite and calcite often seem to be marginal to the main centers of alteration of some of the other copper deposits in porphyry. Inasmuch as calcium largely disappears from the ore porphyry, it seems reasonable to suppose that the solutions deposited some of this calcium farther out. This unusual occurrence will be described in detail in a later paper.

The hydrothermally altered porphyry protore of the Ray district, like that of the Miami district, is characterized by an abundance of quartz veinlets with pyrite and small amounts of chalcopyrite and molybdenite with rather intense sericitization along the walls of the veinlets, accompanied by some disseminated sulfide. Where silicification is not intense, plagioclase especially has been altered to a complex of argillic products. It may logically be inferred that considerable destruction of clay minerals was involved in later silicification and sericitization.

The alteration at Ray resembles that at Miami, but silicification is less prominent and argillic alteration more evident. The argillic alteration can be compared to that at Castle Dome but is not nearly as intense. The late quartz-sericite phase of alteration at Castle Dome seems to have been the main phase at both Miami and Ray.

Chino copper deposit, Santa Rita, New Mexico.—The disseminated copper ores of the Chino mine occur mainly in a granodiorite porphyry stock which intrudes Paleozoic and Mesozoic sedimentary rocks and an earlier mass of quartz diorite porphyry.[21] Ore occurs not only in the porphyry but in the

[21] Spencer, A. C., and Paige, Sidney, Geology of the Santa Rita mining area, New Mexico: U. S. Geol. Survey, Bull. 859, 1935.

FIG. 2. Pseudomorph of sericite after plagioclase. East end of Ely district, Nevada. Crossed nicols × 45.

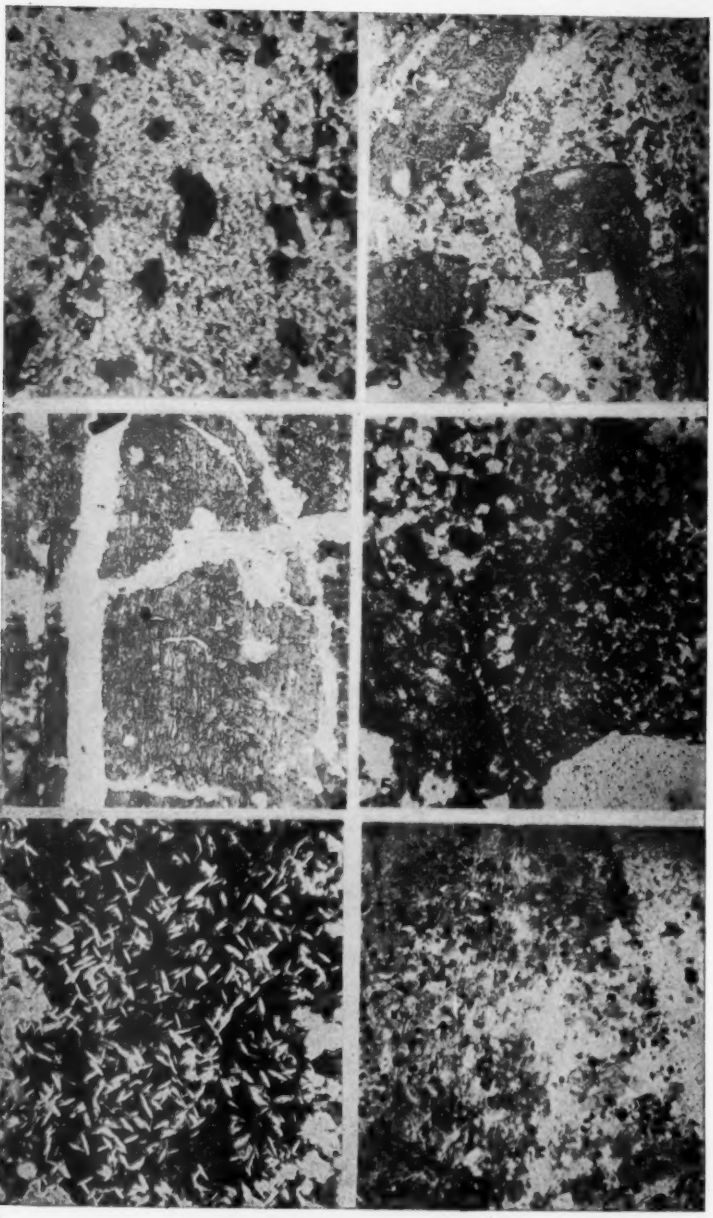
FIG. 3. Pseudomorphs (gray) of allophane after feldspar. Clay pit, Morenci, Arizona. Plain light × 82.

FIG. 4. Sericite veinlets (white) cutting allophane (gray) pseudomorph after feldspar. Clay pit, Morenci. Plain light × 65.

FIG. 5. Quartz-orthoclase groundmass of porphyry in which orthoclase has been converted to allophane (dark gray). Clay pit, Morenci. Plain light × 82.

FIG. 6. Alunite blades (white) in kaolinite pseudomorphs after plagioclase of monozonite porphyry. San Manuel area, Arizona. Crossed nicols × 80.

FIG. 7. Fine-grained aggregate of brown mica, magnetite, quartz, feldspar, titanite and chlorite pseudomorphous after hornblende. Porphyry ore, Nevada Consolidated Mines, Kimberly, Nevada. Plain light × 25.



sedimentary rocks, and hydrothermal alteration has been so intense that identification of the primary character of the rock is often difficult or even impossible. The writer originally examined a series of 29 thin-sections of rocks from the Chino area sent to Professor Frank Grout by George Ordonez, geologist for the Chino mine. They came mainly from diamond-drill holes in the east wall of the present pit. Of them 11 were definitely altered porphyries. The others were altered sedimentary rocks and a few were of rather indefinite character. The alteration of all of them is somewhat similar but only the porphyries were considered in detail because it is possible to be fairly certain of the composition of the original minerals in them. In 1946 a brief visit to the area was made under the guidance of S. G. Lasky of the U. S. Geological Survey who is making a comprehensive survey of the Silver City area. Thin-sections of the rocks from the Bayard area were examined and a few specimens from the Chino pit collected for microscopic study. Meanwhile Professor Paul Kerr has undertaken a detailed study of the alteration for the company.

The porphyries shown by drill cores are generally much bleached and impregnated with pyrite. Some show secondary enrichment and two of the samples are somewhat oxidized. Sericite is abundant in most thin-sections. The primary ferromagnesian minerals have often been entirely destroyed, but the original location of biotite is sometimes revealed by an abundance of rutile. In less-altered rocks chlorite and hydromuscovite replace the biotite. Some sections show an abundance of shredlike mica which is brownish—probably hydrobiotite rather than sericite. In many sections argillic alteration products are abundant even in the absence of weathering. In one moderately altered rock plagioclase phenocrysts are cut by a network of veinlets of beidellite varying to pseudomorphs of beidellite after feldspar. Some areas of kaolinite are cut by peculiar, curving, branching stringers and veinlets of beidellite. In some specimens allophane is abundant with beidellite, the two forming pseudomorphs. Often a small amount of fine, flaky kaolinite occurs as nests in sericite; locally kaolinite forms rather large areas. One thin-section seemed to be a complex of kaolinite, nontronite, and allophane, with some pyrite, quartz, and sericite. Another, which shows intense sericitization, contains white areas, apparently pseudomorphous after feldspar, and composed of a mixture of halloysite and allophane. On the lowest level in 1946, light-gray, highly altered porphyry shows much alteration to clay

FIG. 8. Coarse-grained sericite which replaced a feldspar phenocryst. Bisbee, Arizona. Crossed nicols × 45.

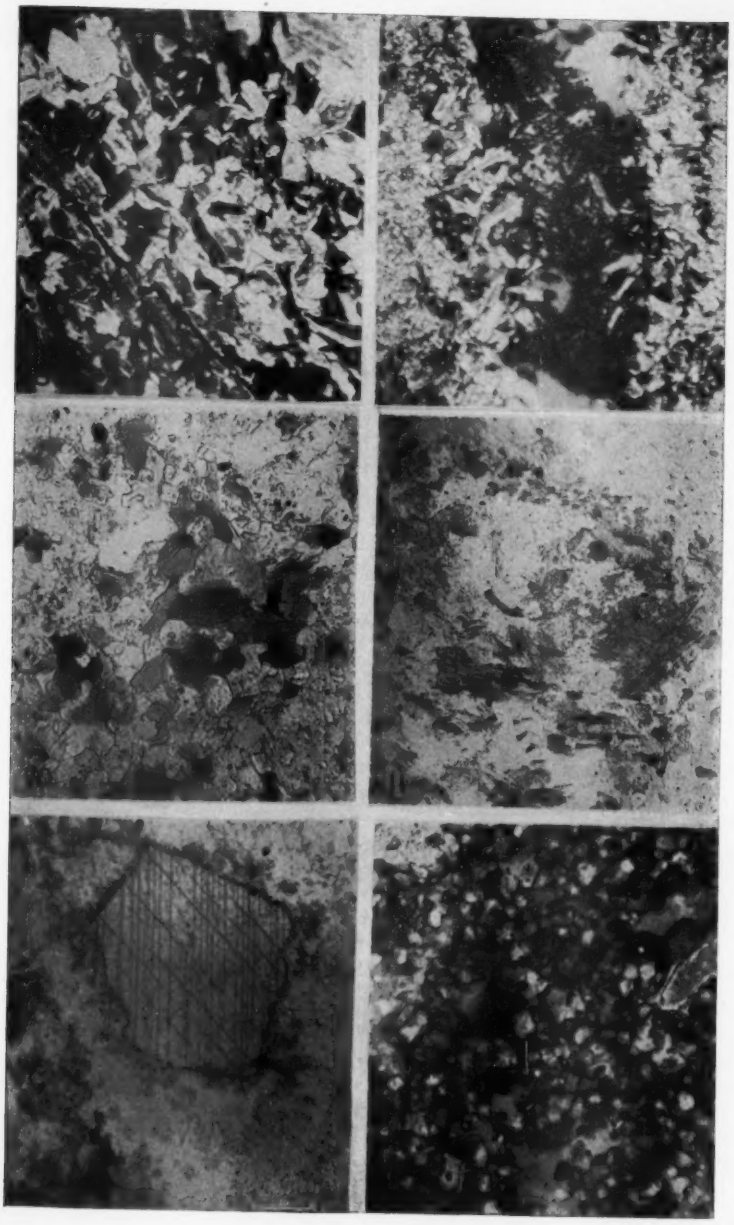
FIG. 9. Nest of kaolinite (dark gray) in quartz-sericite vein. Clay pit, Morenci. Crossed nicols × 82.

FIG. 10. Hydrothermal biotite (dark) disseminated in altered porphyry. Emma Mine, Kimberly, Nevada. Plain light × 82.

FIG. 11. Hydrothermal biotite (dark gray) disseminated in altered porphyry. Utah Copper pit, Bingham, Utah. Plain light × 82.

FIG. 12. Calcite metacryst in altered porphyry dike rock. Bisbee, Arizona. × 45.

FIG. 13. Quartz-orthoclase mosaic which replaced coarser material of granite porphyry. Inspiration Mine, Miami, Arizona. Crossed nicols × 135.



minerals (kaolinite, hydromica, dickite) and sericite. Nearby a light-gray, chalky-appearing rock contains dark-gray quartz-sericite veins. The original rock was much altered to a complex of clay minerals, particularly halloysite and kaolinite with less allophane and dickite. Along the quartz veins sericite has worked outward replacing the argillized rock. The most completely bleached and altered rock shows a confused aggregate of allophane, kaolinite and sericite. Biotite has altered completely to hydromuscovite and other clay minerals with the crystallization of titania as rutile.

A typical analysis of ore furnished by the company shows 2.99 per cent K_2O, somewhat below average for a fresh quartz monzonite porphyry. The CaO is only 0.14 per cent indicating the completeness of destruction of plagioclase and its alteration largely to clay minerals. Lasky [22] believes that the Chino stock is composite and that the alteration may be of two generations separated perhaps by a period of metallization. It is evident that completion of the regional study of the area is a necessary foundation for the unraveling of this complex alteration problem.

Ely district, Nevada.—The problem of hydrothermal alteration in the copper deposits of the Ely district is considerably complex, and the complexity is increased by the fact that geologists are not agreed as to whether there is only one kind of primary porphyry or two of at least slightly different age.[23] The writer is inclined to agree with Spencer that there was only one original type of porphyry. The separation into so-called "Peanut" and "Ore" porphyries is believed to be based on characteristics developed by hydrothermal alteration.

Much of the ore mined in the early years was enriched ore, but at present the greater portion is primary and it is thus possible to avoid the effects of supergene processes in studying the hydrothermal alteration. Greatest copper values do not always coincide with the greatest degree of hydrothermal alteration, but in general values do fade out with decreasing alteration.

The fresh porphyry is described in detail by Spencer. The rock varies from monzonite to quartz monzonite and is usually prophyritic with large and abundant orthoclase phenocrysts. The groundmass has a porphyritic texture due to small phenocrysts of plagioclase and often of well-formed hornblende crystals. The matrix is finely to coarsely crystalline orthoclase and quartz.

The following summary of the character of the porphyry within the altered area was furnished by Kenyon Richards and J. H. Courtright,[24] geologists of the Consolidated Coppermine Corporation at the time of the writer's visit. Two facies of porphyry are recognized but are believed by them to have been derived from the same primary rock by hydrothermal alteration and are referred to locally as "Ore porphyry" and "Peanut porphyry." "Ore porphyry"

[22] Personal communication.

[23] Spencer, A. C., The geology and ore deposits of Ely, Nevada: U. S. Geol. Survey, Prof. Paper 96, 1917.

Pennebaker, E. N., Geology of the Robinson (Ely) mining district in Nevada: Mining and Metallurgy 13: 163–168, 1932.

Bateman, Alan M., The copper deposits of Ely, Nevada: Copper Resources of the World, 16th Internat. Geol. Cong., 307–321, 1935.

[24] Personal communication.

is more altered, and is usually characterized by complete conversion of feldspars to sericite and kaolinite, ferromagnesians to phlogopite (biotite) and pyrite. Rude granular texture is still discernible though rock is largely replaced by quartz and is traversed by a network of quartz veinlets. "Peanut porphyry" has four recognized degrees of alteration: (1) Unaltered orthoclase; plagioclase altered to kaolinite and sericite, ferromagnesians partly altered to chlorite; sparse disseminations of pyrite. (2) Only borders of orthoclase are altered; groundmass composed of quartz, chlorite and sericite; ferromagnesians partly altered to chlorite. (3) Same as type 2 except that alteration is more advanced; silicification moderate; chlorite; abundant; remnants of granitoid texture discernible. (4) Shear zones; chlorite abundant; quartz stringers closely spaced and crushed; feldspar phenocrysts rarely seen; rock has evidently suffered both premineral and postmineral shearing.

The so-called "Peanut porphyry" in the vicinity of the ore bodies is obviously altered porphyry corresponding to the fresh type found beneath the footwall fault at Kimberly and elsewhere in the district. The orthoclase phenocrysts or their pseudomorphs remain, hence the name "peanut." In the vicinity of the ore bodies, however, the rock has been subjected to fairly intense alteration and commonly is dark gray. Thin-sections show that most of the minerals of the original rock have been highly altered. The primary hornblende has entirely disappeared and now the dark mineral is mainly disseminated light-brown biotite mica (Fig. 10). Some dark mica is a more normal biotite and a light-green variety is probably hydrobiotite. In one thin-section the outline of a large hornblende phenocryst remains but the material is now a complex aggregate of biotite, chlorite, magnetite, feldspar, kaolinite and titanite (Fig. 7). In most thin-sections the brown mica is irregularly disseminated throughout (Fig. 10) and is only in small part pseudomorphus after pre-existing ferromagnesian minerals.

At places the secondary brown mica occurs as coarse books an inch or two across. Through the courtesy of Mr. John Hope, present chief geologist of the Consolidated Coppermines Corporation, the writer was recently furnished the following partial analyses of two samples of brown mica selected to determine whether it should be called phlogopite or biotite.

	SiO_2	Al_2O_3	FeO	MgO
1.	50.60%	18.29%	7.66%	8.04%
2.	43.40	23.21	7.60	8.73

In view of the nearly equal amounts of ferrous oxide and magnesium oxide it should doubtless be referred to biotite and Professor Gruner has verified this by an X-ray determination.

Orthoclase commonly remains little altered but plagioclase has normally been converted to secondary products which include sericite, hydromuscovite, potash clay, kaolinite, and allophane. The groundmass is commonly a fine mosaic of quartz and orthoclase. This mosaic is much finer grained than the quartz-orthoclase groundmass of the fresh rock and scallops the edges of many phenocrysts and threads its way through the original minerals in a manner suggestive of its later origin. The writer reached the conclusion that

it represented mainly a recrystallization of the original rock rather than large-scale introduction of quartz and orthoclase. Later it was noted that Spencer had come to this conclusion in 1917,[25] as is shown by the following quotation: "The orthoclase of the normal groundmass, and the quartz which accompanies it, have been dissolved and redeposited as an aggregate of finer grain, commonly with the addition of brown mica and characteristically with the addition of distributed grains of pyrite and chalcopyrite."

In addition to the alteration products already noted, smaller amounts of calcite, epidote, rutile, leucoxene, and beidellite were noted. The clay minerals have usually been attributed to weathering or secondary-enrichment effects. At least in part this is not true because stringers and veinlets of sericite were observed cutting kaolinite in pyritic ore from the Ruth pit. The sericite is later than kaolinite and there is neither weathering nor secondary enrichment; therefore, kaolinite must be hydrothermal. In fact most of the thin-sections studied were from primary ore containing pyrite and chalcopyrite and lacking evidence of enrichment or weathering.

The so-called "Ore porphyry" at Ely furnishes most of the difficulty involved in the question as to whether or not there is one or two original types of intrusive as noted above. The typical "Ore porphyry" is a light-gray, finely granular rock with fairly abundant well-disseminated pyrite and less abundant chalcopyrite. Light-brown mica is fairly abundant in some facies, but lacking in the common type. Some areas of this rock consist essentially of a quartz-sericite-sulphide complex in which no recognizable primary mineral remains. More common is a complex alteration in which many of the alteration products found in the "Peanut" type occur; but the fine-grained quartz-orthoclase mosaic makes up the larger portion of the rock. Generally the evidence is fairly good that the alteration to sericite, chlorite, brown mica and other products preceded the quartz-orthoclase introduction and recrystallization. In the most extreme example noted, the light-gray "Ore prophyry" consisted of quartz, calcite, and sulphide. In this instance alteration has gone so far that one may well suspect that the material is actually vein deposition. No certain method of distinguishing one from the other is known. In one thin-section a quartz vein makes up a considerable portion of the thin-section. Zoned plagioclase phenocrysts have central cores of oligoclase and rims of sodic oligoclase or albite, and lie in a groundmass of albite and orthoclase. The so-called "Ore porphyry" is believed to represent rock so intensely altered by hydrothermal solutions that its original nature is destroyed. Unaltered "Ore porphyry," as distinct from the "Peanut" type, is unknown insofar as the writer was able to determine.

In Spencer's [26] paper several rock analyses are cited and furnished some evidence of chemical changes. Silica is not radically changed except in a siliceous variety of ore which probably corresponds to the rather typical "Ore porphyry" which shows an apparent gain of 32.3 per cent in silica content. Alumina shows some decrease with increasing silica. Iron, magnesia, lime, and soda decrease, especially lime, which is relatively high in the

[25] Op. cit., p. 56.
[26] Op. cit., p. 57.

fresh monzonite porphyry (6.60 per cent) and shows only a trace in a siliceous variety of porphyry ores. Potash shows a large increase in all varieties corresponding to the importance of secondary orthoclase and of sericite in some of the most intensely altered ore-bearing rock.

Rock alteration and ore are not necessarily coincident in the district. It is fair to say that ore never occurs in unaltered rock, and perhaps in a general way within the ore bodies the more intensely altered rock carries the best ore values. However, at places in the district intensely altered rock is not accompanied by ore. For example, east of the Ruth pit in Lane Valley is highly altered porphyry, now essentially a quartz-sericite rock (Fig. 2) which originally contained pyrite, now altered to jarosite. Available data do not indicate whether ore is related to specific features of the alteration; possibly detailed mapping of the alteration pattern might lead to definite conclusions in this matter. Further work on this point seems desirable.

The alteration in the Ely deposits may be briefly characterized as follows: One facies consists of conspicuous secondary brown mica, with less sericite, and with other alteration products. Less commonly some ore consists mainly of a quartz-sericite-sulphide complex which has almost completely replaced the original porphyry. The second abundant facies often intimately associated with that described above consists of a fine-grained quartz-orthoclase aggregate more or less flooding the rock and causing it to appear fresh and less altered, whereas actually is represents thorough alteration. A complex of lesser alteration products associated with this facies consists of sericite, biotite, calcite, kaolinite, chlorite, allophane and rutile. Pyrite and chalcopyrite are disseminated throughout.

Argillic alteration is usually not conspicuous at Ely but careful study of thin-sections often reveals kaolinite as an alteration product of plagioclase. Several other clay minerals were determined in individual sections but are not characteristic.

Morenci, Arizona.—The disseminated copper ore at Morenci is now developed by a large open-pit which includes much of the central part of the porphyry stock. It is probable that this ore body will become the type example of intense argillic and sericitic alteration with the introduction of copper. Insofar as could be seen in brief visits to the pit the ore represents a rather remarkably uniform hydrothermal alteration of a considerable portion of the stock. The rock in the pit is characterized by a very light gray color resulting from the alteration of feldspar to clay minerals and sericite, and by the complete destruction of the ferromagnesian minerals. Quartz veins are lacking in many portions of the pit; locally they are important but in the pit as a whole silicification and vein filling with quartz seem slight.

Much of the ore in hand specimen is chalky in appearance. In many areas there are extensive seams and fractures bordered by a darker-gray zone (Fig. 14) which appears to have been formed by material soaking in from the small fractures filled with quartz and pyrite. This gray zone looks siliceous but actually is a zone of intense sericitization. Since these fractures cut the highly argillized porphyry it can scarcely be denied that sericitization is later than argillization, contrary to the usual belief.

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A suite of specimens collected for microscopic study included several representing typical ore as exposed in 1945 and 1946, and also igneous rocks of areas adjacent to the pit, mostly highly altered. These specimens were supplemented by drill cores from various depths and locations below the commercial ore body obtained through the courtesy of L. E. Reber, Jr., W. C. Lawson, and the Phelps-Dodge Corporation.

The light-gray porphyry ore is intensely altered. Ferromagnesian minerals have disappeared but clusters of rutile reveal their former location. Plagioclase phenocrysts have altered, often completely, to pseudomorphs of allophane and halloysite or sericite and hydromuscovite (Figs. 3 and 4). The groundmass has altered largely to halloysite in the most altered specimens. Small veinlets contain quartz, sericite and pyrite, and less commonly chalcopyrite, molybdenite and supergene chalcocite. Pyrite is disseminated through-

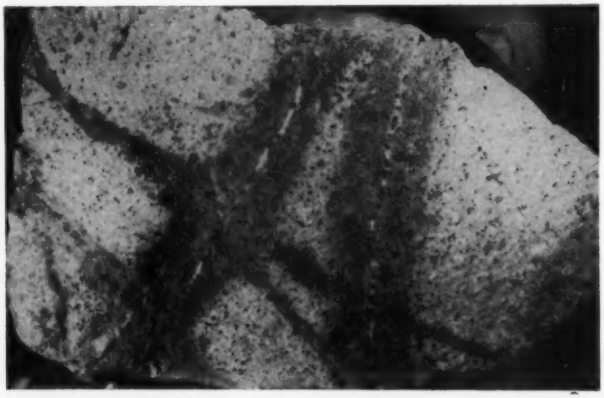

FIG. 14. Minute quartz-veinlets with wide borders of sericite which replaced argillized porphyry. Clay pit, Morenci, Arizona. Three fourths natural size.

out and sericite is frequently coarser grained around clusters of pyrite grains. Many pseudomorphs of allophane after feldspar are cut by veinlets of sericite and hydromuscovite (Fig. 4). The most intense sericitization as noted above occurs in gray borders of quartz-pyrite veinlets (Fig. 14). The rock is somewhat tougher than the chalky-gray argillized rock and the darker-gray zones are mainly a mat of sericite with some quartz. Some masses show small dark spots which are nests of coarse sericite and appear as flakes in the cores of altered feldspar crystals. Veinlets of quartz and pyrite may contain areas of very fine grained kaolinite (Fig. 9) with hydromuscovite as coarser blades.

A drill core from a depth of 725 feet near the west end of the pit shows a highly altered porphyry with yellowish clay pseudomorphs after plagioclase. These pseudomorphs consist mainly of kaolinite, an identification which Dr. J. W. Gruner kindly verified by an X-ray determination. Embedded in the kaolinite are a few blades and plates of sericite and hydromuscovite; at places

veinlike stringers of sericite cut the kaolinite. Some large plagioclase phenocrysts which have escaped alteration to kaolinite show zonal structure outlined by a concentration of sericite in certain zones. Biotite grains have been largely altered to chlorite, or green mica (hydrobiotite?) with the elimination of titanium to form leucoxene. The groundmass was originally a quartz-orthoclase mosaic with some grains of plagioclase and biotite. It has been severely altered to kaolinite, allophane, beidellite and a little montmorillonite (Fig. 5). Veinlets contain pyrite, chalcopyrite and adularia.

Thin-sections of several other drill cores from beneath the supergene ore were examined. Some are not as intensely altered as those described above but all show some clay alteration and various degrees of sericitization. In those showing less alteration some biotite remains with part alteration to light-brown mica, chlorite, muscovite and rutile. Where the alteration of biotite is fairly intense only colorless mica (muscovite or sericite) with inclusions of rutile remain. Areas of kaolinite with a few embedded flakes of sericite which do not have the appearance of remnants seem characteristic in less-altered rocks. These flakes are probably later, for in more intensely altered rocks veinlets of sericite are common as noted above. Many of these rocks contain considerable flaky material which is coarser grained than kaolinite but of lower birefringence than sericite; probably it is both hydromuscovite and potash clay.

Specimens of altered granite porphyry were also collected from the vicinity of the pit at Morenci but remote from copper mineralization. Extensive development of allophane and halloysite was also found in these rocks. At very high magnification allophane seems to be disseminated in a matrix of halloysite. In one slide a quartz vein is bordered by sericite suggesting a later origin of sericite as in the pit.

Fresh porphyry is apparently unknown in the Morenci area; but a dike of quartz monzonite porphyry in diorite along Chase Creek below the pit gives a fair idea of the nature of the fresh porphyry for comparison with the rock in the pit. It consists of small phenocrysts of plagioclase (andesine) and biotite, and a fine-grained groundmass of quartz and orthoclase plus accessory zircon and sphene. There has been considerable alteration and flakes and shreds of sericite and hydromuscovite are abundantly disseminated throughout. A few biotite grains remain unaltered but most are partly altered to hydrobiotite (?) and chlorite with the elimination of rutile and leucoxene. There is also some dusty allophane, in orthoclase and where the argillic alteration is most severe orthoclase may be altered to halloysite.

Briefly the alteration of the porphyry at Morenci is characterized by an intense and complex argillic alteration in which kaolinite, allophane, and halloysite are most abundant but hydromuscovite, beidellite, and nontronite were also recognized. With this alteration, and later, at least in part, is extensive sericitization which, in its most intense expression, cuts the kaolinized rock along intersecting fractures on a large scale in the broken ore. Quartz is not prominent. Small veinlets fill fractures along which sericitization is intense and some secondary quartz was doubtless released by the complex alteration but actual introduction of silica is certainly at a minimum. A con-

siderable amount of chemical work is desirable in connection with the present studies but only a few data are available. The following compiled data are pertinent in connection with the argillic alteration:

SOME CHEMICAL DATA ON MORENCI ALTERATION

	1	2	3
SiO_2	68.04%	65.4 %	Not determined
Al_2O_3	17.20	16.20	Not determined
MgO	1.05	0.45	Not determined
CaO	2.21	0.55	Not determined
Na_2O	5.33	Not determined	0.19
K_2O	2.65	Not determined	2.60

1. Relatively fresh quartz monzonite porphyry. U. S. Geological Survey, Prof. Paper 43, p. 81.

2. Composite diamond-drill samples of Clay ore body. Furnished by the Morenci Branch, Phelps-Dodge Corporation.

3. Alkali determination of light-gray porphyry ore. Analyst: Lee C. Peck, Rock Analysis Laboratory, University of Minnesota. Expense defrayed from research funds of the Graduate School.

The absence of silicification on a large scale is verified. To the extent that quartz has been introduced, it has been balanced by a loss of silica in the strictly argillic portions of the rocks.

The decrease of MgO, CaO, and Na_2O is so great that the destruction of silicates containing these minerals is verified. Potassium in the sample of porphyry ore is essentially the same as in Lindgren's [27] fresh porphyry. The potassium occurs mainly in the form of sericite. If all of the potassium is alloted to sericite the percentage in the ore specimen analyzed is 22.03. The 16.2 per cent Al_2O_3 of the drill samples would be equivalent to 19.5 per cent kaolinite after subtracting the necessary alumina for the sericite. The actual clay minerals include allophane, halloysite and kaolinite, but the calculated amount of clay mineral is of the same order no matter which clay mineral is assumed to be present.

San Manuel copper deposit, Arizona.—The geology of the San Manuel area has been briefly described in a recent preliminary report,[28] and it is necessary here only to point out the aspects bearing on hydrothermal alteration. Much of the area is so deeply buried beneath a thick cover of Gila conglomerate and alluvial-slope deposits that the geology of the copper-bearing rocks is known mainly from drilling. The occurrence of the copper is similar to that of other disseminated deposits. The two important rocks affected are a pre-Cambrian quartz monzonite (Oracle granite) and a later monzonite porphyry probably to be correlated with some of the other copper-bearing porphyry intrusives of Arizona. To date there appears to be no consistent difference in mineralization between the two rocks.

The San Manuel area is somewhat unique in the rather well defined areal distribution of four fairly distinct types of hydrothermal alteration. These

[27] Lindgren, Waldemar, The copper deposits of the Clifton-Morenci district, Arizona: U. S. Geol. Survey, Prof. Paper 43, p. 81, 1905.

[28] Schwartz, G. M., Geology of the San Manuel area, Pinal county, Arizona: U. S. Geol. Survey, Strategic Minerals Investigations, Preliminary Maps 3–180, April 1945.

types have their counterparts to a considerable extent in other districts, but no other district, to the writer's knowledge, has so many and such easily recognized areas for each type. The distribution as shown by outcrops and preliminary drilling is shown in the report referred to above. The four types are briefly characterized.

Type 1. The most intense rock alteration occurs in a small oval area about 700 by 800 feet, with a probable but unknown extension eastward. The monzonite porphyry and a small amount of quartz monzonite in this area have been completely altered, and the weathered outcrops are of a prevailingly light-gray color, somewhat stained in places with iron oxide. This rock consists mainly of hydrothermal clay minerals, especially kaolinite and alunite (Fig. 6). This zone has not been penetrated at depth by drilling, so the nature of primary mineralization is unknown. The alteration, however, is similar in some ways to that at Morenci and Chino.

Type 2. This alteration somewhat resembles Type 1, but is characterized by high pyrite at depth and a very red color in the oxidized zone. Hydromuscovite is more abundant than kaolinite and alunite is often lacking. Chlorite occurs in small amounts and secondary rutile is prevalent. Alteration of the original rock is complete except for the quartz. This type of alteration with the formation of clay minerals, high pyrite and low copper has its counterpart in the protores at Morenci, Ray, and Chino.

Type 3. Along the south side of the area of Types 1 and 2 is a narrow zone with a steep dip to the south which is characterized by intense alteration with a flooding by sericite with important amounts of chalcopyrite and pyrite at depth. At the surface, the rock is dark brownish-red, rather than brick-red as in the surface exposure of Type 2. Chrysocolla coats even the most minute fracture surfaces of the better-mineralized rock. At depth the rock is essentially a quartz-sericite-pyrite-chalcopyrite aggregate, with chalcocite replacing most of the chalcopyrite in the secondary sulphide zone. Biotite has disappeared from most of the mineralized rock, but pseudomorphs of muscovite and chlorite with secondary rutile are not uncommon. There are many minor alteration products including kaolinite, hydromuscovite, beidellite, leucoxene, rutile. Sericite clearly cuts the argillic products as veinlets and stringers and is, at least in part, later than the clay minerals. This sericitic alteration is similar to that found in most disseminated copper deposits.

Type 4. A marginal, less intense alteration, is found in a single outcrop south of the area of better-copper mineralization. This material has now been penetrated by thousands of feet of drilling. It usually assays from 0.10 to 0.30 of a per cent copper. Drill cuttings of the unweathered porphyry appear fresh under a hand lens, but in thin-section the groundmass especially is a complex of alteration products, with secondary biotite, hydrobiotite, epidote, zoisite, and chlorite more abundant than in other types. Similar alteration occurs on the north side of the area of Types 1 and 2, but here most of the plagioclase and biotite phenocrysts are partly replaced by epidote, sericite and secondary biotite.

This marginal alteration south of the main copper-bearing zone has much in common with the "dark" porphyry at Bingham, Utah, and the biotitic

alteration at Ely, Nevada. There is less introduced brown mica at San Manuel but the writer has studied thin-sections from San Manuel and Bingham that are almost identical.

Sacramento Hill, Bisbee, Arizona.—The Sacramento stock which originally contained a large porphyry ore body in the zone of secondary sulfide enrichment furnishes an excellent opportunity to study rock alteration in relation to the ore body. The Sacramento ore body lies entirely on the south side of the Dividend fault with the probability that exposures north of the fault represent much deeper erosion of the stock, since the Paleozoic limestones remain only south of the fault within the mineralized area.

Ransome [29] describes nearly fresh porphyry from Escabrosa Ridge which is believed to be the equivalent of the highly altered porphyry of the Sacramento stock. It is classified as a granite porphyry with phenocrysts of quartz, orthoclase and less abundant oligoclase embedded in a groundmass containing a few flakes of biotite and a microgranitic aggregate of quartz and orthoclase.

A favorable opportunity to obtain hydrothermally altered porphyry free from effect of weathering is presented in the occurrence at a 500-level drift passing beneath the Sacramento pit. The porphyry from this level contains abundant disseminated pyrite with sericite, hydromuscovite, kaolinite, allophane and alunite, all as products of the hydrothermal alteration of the feldspar. Biotite is almost completely altered to sericite with some leucoxene released during the breakdown and occasionally also some chlorite and kaolinite. Sericite occurs as isolated blades or streaks in kaolinite. The sericite is believed to have formed later than the kaolinite. The identity of this kaolinite was verified by an X-ray determination.

North of the Dividend fault the porphyry of the Sacramento stock is conspicuously red at the surface due to oxidition of pyrite, but the rock is essentially barren of copper. A network of quartz veinlets is characteristic. Near the top of Copper Hill a shallow shaft penetrates unoxidized pyritized porphyry which is characterized by extreme sericitization of feldspar (Fig. 8) and biotite. The pseudomorphs of the latter contain clusters of rutile. Locally in the sericite are nests of very minute flakes of kaolinite. Quartz is filled with minute inclusions of allophane. On the surface near the crest of the hill rock is exposed that is essentially similar except pyrite has oxidized to jarosite and limonite.

Specimens of porphyry were collected from dikes and irregular intrusives that radiate out in a rough way from Sacramento Hill and penetrate the limestones in which the principal Bisbee ore bodies occur. Other specimens from widely separated areas underground were kindly furnished by Carl Trischka. It was hoped that these dikes might give a somewhat adequate idea of the less-altered porphyry. This hope was not realized but instead a variable sort of alteration was revealed. Although some of these rocks appear fresher in hand specimen than those from the Sacramento stock, they are in fact highly altered and in some calcite (Fig. 12) is the most abundant altera-

[29] Ransome, F. L., The geology and ore deposits of the Bisbee quadrangle, Arizona: U. S. Geol. Survey, Prof. Paper 21, 1904.

tion product. It is accompanied by sericite, hydromuscovite, kaolinite and allophane. Other specimens show an abundance of epidote with less calcite and extensive alteration to sericite, hydromuscovite, kaolinite and chlorite with considerable disseminated pyrite. Epidote developed, particularly in biotite which was fairly abundant in the original porphyry. Biotite is usually completely altered to pseudomorphs of variable type but consisting of one or more of the following minerals: chlorite, epidote, hydromuscovite, muscovite, calcite, pyrite, rutile and leucoxene. In these porphyries plagioclase has been converted to a very fine mat consisting mainly of sericite, hydromuscovite, and kaolinite in various proportions; in several specimens hydromuscovite is much more abundant than sericite. Calcite occurs locally. Of eleven specimens from the outlying intrusives studied in detail in thin-section, only three failed to show considerable amounts of either calcite or epidote or both. Calcite and epidote are not common alteration products in the copper porphyries, but the dikes at Bisbee are intruded into a very thick series of limestones often mineralized to a high degree. It seems evident, therefore, that the hydrothermal solution picked up a load of calcium carbonate in passing through the limestones and on entering the porphyry dikes replaced part of the porphyry with calcite or by reaction formed epidote. This procedure contrasts with the alteration of the main stock which is dominantly sericitic with calcite of no importance as a hydrothermal product.

The dike rocks show some of the most extensive alteration to hydromuscovite found in any of the porphyries studied in this project. Sericite is correspondingly less conspicuous and kaolinite is usually abundant. It seems probable that the hydrothermal solution exchanged some of their potash for calcium in traveling through the limestones and thus altered feldspars to clay minerals in the absence of sufficient potash to form sericite. In the Sacramento stock, where the solution presumably did not pass through limestone, sericitization is conspicuous, as noted above.

Cananea, Mexico.—Through the courtesy of Mr. Albert Mendelsohn, General Manager of the Cananea Consolidated Copper Company, and of Warren Woodward, Chief Geologist, the writer was able to make a brief visit to Cananea and collect specimens for microscopic study from the large open-cut started during the war. The location of the pit above the Colorado pipe [30] makes it of unusual interest in the study of the hydrothermal alteration.

As in other disseminated copper deposits the alteration is intense. The rocks involved were originally andesitic volcanics and monzonite porphyry. Bleaching has been so complete that the white walls of the pit are dazzling in the summer sun. It is difficult to imagine dark-gray primary rocks so completely bleached.

Thin-sections of typical ore specimens show that the rock has been intensely sericitized; in fact, it seems to the writer to represent the most complete sericitization seen in any disseminated deposit. Other deposits show equally intense sericitization locally, but in the Cananea pit it is not only intense but pervasive. Pyrite is fairly abundant in most rock. Silicification

[30] Perry, V. D.: Copper deposits of the Cananea district, Sonora, Mexico: Copper Resources of the World 16th International Geological Congress, vol. 1, pp. 413–418, 1935.

is not conspicuous but minute quartz veins cut some portions in an intimate fashion. The general lack of silicification is confirmed by the mill heads which averaged 59.3 per cent SiO_2 for a period of nine months. With the sericite in some parts are considerable amounts of kaolinite and some dusty appearing allophane. Hydromuscovite occurs with the kaolinite in some thin-sections. In some sections of the pit clusters of minute radiating crystals of tourmaline occur in the highly altered porphyry otherwise similar to that described above.

The mineralogical changes are most easily followed in the altered porphyry which usually retains shadows of its original texture. Biotite phenocrysts have been altered to muscovite pseudomorphs with much replacement by pyrite and elimination of leucoxene or rutile. Feldspar phenocrysts have been altered to sericite, hydromuscovite, and kaolinite. The destruction of plagioclase and the resulting solution of lime is shown by the low CaO content of the ore which averages 0.7 per cent. Alunite is a characteristic vein mineral in the Colorado pipe but was not recognized in the altered specimens from the pit. It would be surprising, however, if detailed study of the pit failed to reveal some alunite as an alteration product or vein filling.

In general, the hydrothermal alteration of the porphyry and volcanic rocks in the pit is much like that of the disseminated copper deposits of the United States, with the exception that tourmaline is conspicuous at places in the Cananea pit and is unknown in the other deposits described in this paper.

GENERAL DISCUSSION AND PARAGENESIS.

It is evident from the data presented in this preliminary study of the broad problem of hydrothermal alteration of the "copper porphyries" that the alteration is complex, variable both within individual deposits and from one deposit to another, and that often one dominant facies tends to obscure the others that are present.

The complexity may perhaps best be illustrated by presenting in summary form the hydrothermal minerals recognized with the mineral from which they are known, or believed, to have formed or replaced. The more common products are listed first.

Plagioclase→Sericite, kaolinite, hydromuscovite, allophane, alunite, halloysite, epidote, zoisite, calcite, chlorite, quartz, orthoclase, beidellite, biotite, potash clay, nontronite, montmorillonite, dickite, antigorite, pyrite, chalcopyrite.

Orthoclase→More resistant to alteration but in severe alteration may form most of the above minerals.

Biotite→Secondary biotite, hydrobiotite, chlorite, muscovite (sericite), epidote, rutile, leucoxene, hydromuscovite, calcite, magnetite, pyrite chalcopyrite.

Hornblende→Biotite, hydrobiotite, phlogopite, chlorite, sericite, kaolinite, magnetite, rutile, leucoxene, sphene.

Augite→Hornblende, biotite, chlorite. Probably also several of those listed under biotite and hornblende.

Quartz→Resists alteration but may be replaced somewhat by sericite, orthoclase and perhaps other minerals.

Magnetite→Hematite.

Ilmenite→Leucoxene.

Sphene→Leucoxene.

Zircon→Unaltered.

Apatite→Unaltered in some, destroyed in others.

The general pattern of alteration has certain marked similarities but exceptions appear, often presenting problems that are difficult to explain. Information at present does not permit statement of invariable relations and the writer suspects that evidence will perhaps never justify statements that a particular mineral always acts in a certain way in hydrothermal alteration whether it is a primary mineral or an alteration product. The following remarks therefore state relations that were observed, and different relations may well be found in the future.

Plagioclase feldspar in the porphyries of the disseminated copper deposits is usually of an intermediate variety ranging from Ab_1An_1 toward the albite end. It is highly susceptible to alteration and pseudomorphs of one or more alteration products are characteristic. Sericite, hydromuscovite, kaolinite, allophane, chlorite are among the more important minerals that replace it. It is not uncommon to find the plagioclase almost destroyed whereas fine-grained orthoclase in the matrix may have largely escaped alteration. The conclusion seems inescapable that potassium aluminum silicate is relatively stable with respect to the hydrothermal solutions which have been active in the copper porphyries. On the contrary sodium and calcium aluminum silicate are relatively unstable and yield up their sodium and particularly calcium to solution.

Orthoclase not only resists alteration but, as is well known, much of it is introduced. One of the problems on which more work is needed is the relative importance of introduction and recrystallization in the formation of secondary orthoclase in the disseminated deposits. Many rocks which show secondary orthoclase do not show a corresponding increase in potash. In many cases the writer believes this is due to formation of secondary orthoclase by recrystallization of primary orthoclase as suggested by Spencer for the Ely district. Careful selection of specimens followed by chemical analysis should solve this problem.

Biotite is next to plagioclase in importance in the study of hydrothermal alteration of the porphyries. This is mainly because it is particularly susceptible to change and thus shows the incipient stages of alteration particularly well, as has been noted by previous investigators. One of the first changes biotite undergoes is a recrystallization of phenocrysts of hexagonal outline to an aggregate of smaller interlocking grains, many of a lighter-brown color. Closely allied with this recrystallization is alteration to a light-green mica, presumably hydrobiotite, and to chlorite. Recrystallization and alteration at this and later stages are accompanied by the freeing of titanium, which may appear as leucoxene but usually occurs as clusters of rounded grains and crystals of rutile. This concentration of rutile in altered

biotite areas is so characteristic that the writer has used clusters of rutile as an indication of former biotite or perhaps other ferromagnesian minerals even where the rock is completely altered and bleached. The progressive alteration of biotite is accompanied by bleaching so that former biotite areas now appear as pseudomorphs of colorless mica which may be termed muscovite, or sericite if the latter term is used to signify a secondary muscovite regardless of texture. Much biotite alters to chlorite but this seems a transitory stage as chlorite is distinctly subordinate in highly altered rocks. Epidote has also been observed as pseudomorphs after biotite as has hydromuscovite.

It is not always possible to determine to what extent secondary biotite and brown mica are a result of alteration of primary biotite. It is certain, however, that at Bingham, Ely, and probably at San Manuel to a less degree, some brown mica is introduced. At Bingham altered hexagonal plates of biotite can be recognized in the mass of brown mica of the "dark" porphyry, but the greater part are flakes of mica which have replaced the porphyry in general. At Ely brown mica (biotite) has replaced other minerals such as plagioclase, hornblende and the groundmass of quartz and orthoclase. Biotite is not important in the unaltered porphyry at Ely; therefore the brown mica is entirely hydrothermal. At San Manuel complex biotite alteration with the probable formation of secondary biotite and hydrobiotite in the groundmass is characteristic of the hanging wall or marginal alteration of the porphyry. In the more intense stages of alteration both primary and hydrothermal biotite are destroyed.

Sericite has always been considered the most characteristic alteration product in the copper porphyries and this remains true even though it is now recognized that the alteration is much more complex than was originally believed. In most deposits sericite is a relatively late mineral and the copper values may be closely associated with it. Where argillic alteration is important as at Castle Dome, Morenci, Chino, and San Manuel, veinlets and stringers of sericite cut the argillized rock in a manner which leaves no reasonable doubt that it is later. This may be seen in hand specimens as well as in thin-sections at Castle Dome, Chino and Morenci.

At San Manuel as far as present evidence goes, there is a very definite association of sericite and copper. Most rock with good copper values is flooded with sericite; most low-grade rock has a dominance of other minerals. Pyrite is particularly abundant in the hydromuscovite alteration of the footwall. Sericite is not necessarily a dependable indicator of values in other copper districts. It probably is in some and probably not in others. It seemed to the writer that the most highly sericitic rocks of the Sacramento stock at Bisbee and also at the eastern end of the Ely district were pyritic but essentially barren of copper. More detailed work needs to be done on this relationship. At Ajo an early orthoclase alteration was extensive, but the copper mineralization is associated with later sericite and other alteration products.

It has been more or less taken for granted that minerals of the clay group in disseminated copper deposits were the result of weathering or of sulphuric acid active during secondary enrichment. Some geologists, notably Ransome, Paige, and Spencer, had called attention to the hydrothermal kaolinite and

halloysite in these deposits, but not much attention seems to have been paid to these reports. The development of the Castle Dome deposit and exploration of the San Manuel claims during the war brought out very clearly that argillic alteration was very important and furthermore occurred in such a manner that the origin of clay minerals as hydrothermal products was indisputable. With Ransome and Paige's reference to kaolinite and halloysite in mind, thin-sections of porphyries from most of the other deposits were examined with particular reference to clay minerals. The following criteria were used in classifying the clay minerals as hydrothermal:

1. In so far as possible, specimens were used which were free from weathering and secondary enrichment so that regardless of other evidence the minerals were either primary igneous rock minerals or a result of hydrothermal alteration.

2. If undoubted hydrothermal minerals such as sericite, quartz, pyrite were later (that is cut the clay minerals as veinlets) the clay minerals were judged to be hydrothermal.

3. The occurrence of well-formed grains, crystals, flakes, or blades of sericite or biotite in clay minerals was considered indicative of a later origin of the sericite or biotite. If sericite was earlier than the clay minerals it should occur as remnants in the fine-grained clay.

At Castle Dome, particularly, the alteration is intense and on a rather large scale so that veinlets of quartz and sericite are clearly later than hydrous mica, kaolinite and beidellite. At Morenci intense alteration to allophane, hydromuscovite, halloysite and kaolinite was followed by sericitization at places along a network of fractures and minute veinlets. Similar alteration also occurs in the Chino deposit.

SUMMARY OF THE HYDROTHERMAL FACIES OF VARIOUS DEPOSITS.

It may be helpful in summary to classify the various disseminated copper deposits on the basis of the dominant and less dominant hydrothermal facies.

Ajo: Quartz-orthoclase alteration dominant; less dominantly sericite, chlorite, and albite.

Bagdad: Mild early stage of albite, biotite, chlorite, sericite followed by a mild but dominant quartz-orthoclase stage accompanied by pyrite and chalcopyrite.

Bingham: Two distinct kinds of ore.

"Dark" porphyry: Biotite dominant, accompanied by hydrobiotite, sericite, hydromuscovite, kaolinite and allophane; clay alteration fairly prominent in this alteration.

"Light" porphyry: Sericite and quartz-orthoclase alteration dominant accompanied by hydromuscovite, kaolinite and allophane. In most intense alteration quartz may become decidedly dominant; this is the latest stage.

Bisbee (Sacramento Hill): Quartz-sericite dominant, accompanied by hydromuscovite, kaolinite, allophane, alunite, chlorite.

Castle Dome: Early mild stage,-sericite, epidote, clinozoisite, chlorite, calcite. Later, a dominant argillic alteration to hydrous mica, beidellite, kaolinite, leucoxene, followed by intense quartz-sericite alteration along fractures.

Chino: Argillic alteration dominant with extensive sericitic alteration. Important minerals are kaolinite, halloysite, allophane, nontronite, hydromuscovite, beidellite, quartz, hydrobiotite, chlorite, rutile, alunite.

Ely: Complex.

Dark-gray altered rock (Peanut poryhyry): Brown mica (biotite) dominant, accompanied by hydrobiotite, chlorite, sericite, hydromuscovite, potash clay, kaolinite, allophane, quartz-orthoclase groundmass.

Light-gray altered rock (Ore porphyry): Quartz-orthoclase dominant accompanied by fairly important sericite, and less important brown mica, chlorite, calcite, kaolinite.

Miami: Alteration of porphyry ore was used for comparison but alteration of Pinal schist is similar.

Quartz-sericite dominant accompanied by quartz-orthoclase, chlorite, hydromuscovite, kaolinite, halloysite, nontronite; clay alteration earlier, at least in part, than sericite.

Morenci: Argillic alteration dominant, consisting of allophane, halloysite, hydromuscovite, kaolinite, beidellite, chlorite, followed by fairly intense sericitization particularly along fractures.

Ray: Alteration of porphyry was used for comparison.

Sericite with less quartz dominant and later than a fairly intense argillic alteration including hydromuscovite, kaolinite, halloysite, allophane, chlorite. Copper values associated with sericite-quartz phase.

San Manuel: Four distinct types of alteration rocognized.

1. Kaolinite-alunite, accompanied by quartz, sericite, hydromuscovite, halloysite, beidellite, allophane, montmorillonite, leucoxene, chlorite.

2. Hydromuscovite-pyrite, accompanied by alunite, kaolinite, rutile, chlorite, sericite, rutile, allophane.

3. Sericite-quartz-pyrite-chalcopyrite, accompanied by kaolinite, hydromuscovite, beidellite, rutile, leucoxene, rutile.

4. Marginal biotite type. Secondary biotite, hydrobiotite, hydromuscovite, epidote, zoisite, chlorite, sericite, calcite, rutile, leucoxene, kaolinite, halloysite, allophane potash clay.

Scattered references to zones of alteration occur in this paper. It is not expected of a preliminary study to reveal the details of alteration or mineral zoning. At San Manuel where the writer has done detailed work the four zones are fairly well defined though by no means completely outlined or understood. It seems to be more or less generally a fact that in the porphyry copper deposits the area of intense sericitic alteration is surrounded by a fading zone of propylitic alteration. In some districts there is a fairly good basis for this view. In others it is not easy to recognize such a zone and it assuredly is marked at places by other kinds of alteration. Scattered evidence gathered by the writer suggests that calcite in addition to chlorite and epidote often occur in the marginal zone. The leaching of calcium in the

copper zone with some deposition farther out seems to explain the origin of the calcite.

There is some question whether areal zones will prove to be as distinct in most of the porphyry copper deposits as are the stages of alteration. For example at Castle Dome quartz and sericite are superimposed on an intense argillic alteration of the porphyry. At Ajo an earlier orthoclase alteration is followed by a complex alteration involving sericite, epidote, chlorite and albite which affected much the same area. The areal relations of the dark and light facies of the Utah Copper Mine are known only in a general way. A detailed study of their relations and that of any marginal facies which might be revealed would seem particularly desirable.

RELATION OF COPPER MINERALS TO ALTERATOIN FACIES.

The relation of the copper content to the various alteration products is a matter of considerable importance but one not easily determined or simply stated. Here too it is not expected of a preliminary study to establish the relations with finality, but some facts do appear.

First of all it must be recognized that there is a distinct difference in the relation of copper content to hydrothermal alteration depending on whether the commercial ore is primary or a result of secondary enrichment. In the former case the relationship between the copper (usually in the form of chalcopyrite) and the hydrothermal minerals is direct. In the case of enrichment, however, it is commonly true that much of the copper content is related to the distribution of pyrite in the primary ore with chalcopyrite also playing a role if it occurs in appreciable amounts in the primary ore. Thus in deposits with very low grade protores such as those at Miami, Ray and Morenci, the relation of pyrite to the hydrothermal minerals is the important feature, the copper minerals being related to specific hydrothermal facies or stages only in a secondary manner. In deposits such as San Manuel and Castle Dome the bulk of the highly pyritic rocks is outside the ore zones which are largely determined by the distribution of primary chalcopyrite, although enriched pyritic ore does exist, particularly at San Manuel.

In primary ores the evidence seems fairly conclusive that the chalcopyrite was introduced largely with the sericitic mineralization; less commonly with biotite where it is important, as in portions of the ore zones at Bingham and at Ely. At San Manuel careful studies of a great many drill holes penetrating a lean hanging wall, the ore zone, and a pyritic footwall show a direct relation of chalcopyrite to sericite. Even in deposits where another mineral dominates the alteration, the ore may be more closely related to sericite. Thus at Ajo, where orthoclase is the most abundant secondary mineral, Gilluly [31] finds that the paragenetic series indicates that copper, mainly chalcopyrite, was largely introduced after orthoclase, during the formation of sericite, chlorite and other alteration products.

[31] Gilluly, James, The Ajo mining district Arizona: U. S. Geological Survey, Prof. Paper 209, p. 75, 1946.

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It does not follow that sericitic alteration always means a high copper content. Plenty of examples of a sericite-pyrite mineralization without copper exist, some noted in the descriptions of districts in this paper. It might be stated with some assurance that the absence of sericitic alteration in a region is unfavorable to the occurrence of disseminated copper deposits.

Further generalizations on the significance and distribution of the hydrothermal alteration facies in the porphyry copper deposits must await the results of more detailed studies in a number of districts. The distribution of the alteration facies must be studied in connection with detailed geologic mapping, both within the ore bodies and outward beyond their margins. Determination of the igneous history of a considerable area is fundamental to the proper interpretation of the alteration as well as of the metallization. The detailed study of the Ajo region recently published by the U. S. Geological Survey (Professional Paper 209) and the comprehensive program being carried on in the Silver City district of New Mexico by S. G. Lasky of the Survey are examples of the type of work that should be carried on in other districts. Careful study of the data obtained in relation to the distribution of copper and the metals associated with it is likely to lead to interpretations of considerable value in future exploration and development of porphyry copper deposits. The value in exploration of an understanding of the relation of copper content to the alteration facies has been amply demonstrated at San Manuel.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINN.,
April 7, 1947.

THE BERYL RESOURCES OF CONNECTICUT.

EUGENE N. CAMERON AND VINCENT E. SHAININ.[1]

ABSTRACT.

In 1942–44, about 120 Connecticut pegmatites were examined for beryl and other minerals during investigations by the Federal Geological Survey. Most of the pegmatites lie in the Middletown district, occurring principally in the Bolton schist and Monson gneiss. The pegmatites range from distinctly zoned bodies to those that are essentially uniform mixtures of the component minerals. Beryl in the zoned pegmatites commonly is present in greater concentration in one or more zones than in others. It occurs in the majority of pegmatites examined, but on the basis of crystal counts only 10 pegmatites, either in whole or in sizable part, average 0.2% or more beryl. Six structural types of beryl deposits are described and illustrated: border-zone, wall-zone, intermediate-zone, pod, fracture-controlled, and disseminated. Some pegmatites contain two or more types.

Grades and tonnages of 14 beryl-bearing pegmatites are tabulated. Total indicated and inferred beryl-bearing pegmatite is 207,885 tons containing 859+ tons of beryl. Most of the beryl is in crystals too small to be economically separable by hand sorting, and barring a marked increase in the price of beryl, milling operations would have to be supported primarily by the yield of salable feldspar, scrap mica, and possibly quartz.

INTRODUCTION.

PROSPECTS of a shortage of beryllium led in 1942–1944 to extensive study and exploration of domestic deposits of beryl, the commercial source of the metal, and during this period the United States Geological Survey investigated many beryl-bearing pegmatites. In Connecticut, between October 1942 and January 1944, about 120 pegmatites were examined for beryl and other minerals. The more promising deposits were mapped and studied in detail, and three beryl properties were explored by the Federal Bureau of Mines in collaboration with the Survey.

The occurrence of beryl in many pegmatites in the state had long been known, but available information regarding grades and tonnages of beryl-bearing pegmatite was scant. The primary purpose of the studies was to select the more promising deposits and to determine, so far as feasible, their tonnages and grades. Beryl production in the past had consisted entirely of crystals large enough to be sorted out by hand, but as there was good reason to believe that reserves of hand-separable beryl were very small, attention was given also to deposits from which beryl might be recovered by milling if a suitable separation process could be developed. Most of the known beryl occurrences in the state were examined during the work, as well as others discovered in the course of investigation of pegmatite-bearing areas.

[1] Published by permission of the Director, U. S. Geological Survey.

Considerable areas in which pegmatites occur remain to be investigated, however, and the following is, therefore, only a partial appraisal of the beryl resources of Connecticut.

The investigations were carried on by Cameron, assisted by Shainin and G. B. Burnett, from October 1942 to July 1943, and were continued by Shainin from July 1943 to January 1944. The studies were under the general supervision of Mr. H. M. Bannerman, to whom the writers wish to express their indebtedness and appreciation for guidance during the field work and for a critical review of the manuscript. Mr. M. F. Fleischer and Mr. D. M. Larrabee, of the Federal Survey, have also reviewed the manuscript and have made helpful comments. This paper has been prepared by the senior author. The terminology used in this report for the various types of lithologic units in pegmatites is that jointly developed and adopted by the various parties of the Federal Survey that have studied domestic pegmatites during the war.[2]

PEGMATITES IN CONNECTICUT.

Most pegmatites in Connecticut that have been mined for mica and feldspar occur in the igneous and metamorphic rocks east of the Connecticut River, and lie within a district 14 miles long and 9 miles wide situated east of the city of Middletown (Fig. 1). This district also contains the more promising known beryl deposits of the state, and the present report is written with particular reference to it. The pegmatites discussed occur in the Monson gneiss and the Bolton schist.[3]

The pegmatite bodies of the district show a wide variety of shapes and sizes. Dikes, sheets, and lenses are most common. Most of the bodies are less than 1,000 feet in length and less than 100 feet in thickness. Some are nearly uniform in thickness and attitude; others have complex shapes. They range in dip from steep to gentle, but most have moderate or steep dips.

The pegmatites show various types of internal structures.[4] Some are essentially uniform mixtures of their component minerals. Others are zoned; that is, the minerals in them are distinctly grouped into structural units of contrasting composition or texture that have a systematic arrangement with respect to the walls of a given pegmatite body. In ideal development (Fig. 2-A), the zones of a pegmatite are successive shells concentric about an innermost zone or core, and the configuration of the zones in a pegmatite body reflects the shape of the body in greater or less degree. Commonly, however, some of the zones within a given pegmatite are incomplete or discontinuous, and there are all gradations between complete zones and those that are developed only along one side or one end of a pegmatite body. These incomplete zones commonly appear as lenses, layers, or pods (Figs. 2-B, 3, 4, 5).

[2] Cameron, E. N., Jahns, R. H., McNair, A. H., and Page, L. R., The internal structure of granitic pegmatites (in preparation).

[3] The distribution of rock formations shown in Fig. 1 follows the Preliminary geological map of Connecticut, by H. E. Gregory and H. H. Robinson, Conn. Geol. and Nat. Hist. Survey, Bull. 7, 31 pp., 1907.

[4] Cameron, E. N., Larrabee, D. M., McNair, A. H., Page, J. J., Shainin, V. E., and Stewart, G. W., Structural and economic features of New England mica deposits, ECON. GEOL., vol. 40, 1945, pp. 379–393.

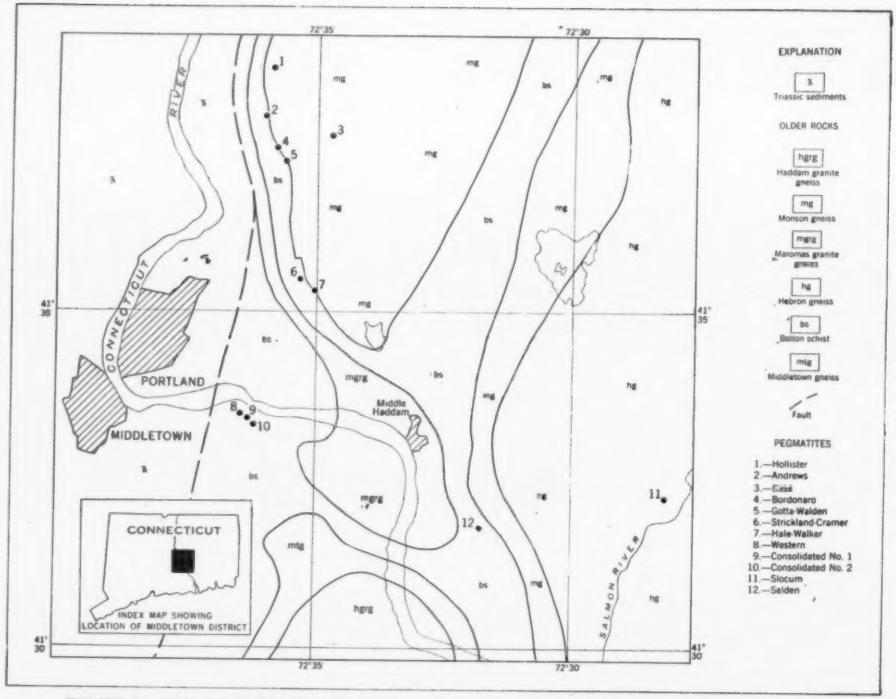


FIGURE 1.—MAP OF MIDDLETOWN DISTRICT, CONNECTICUT, SHOWING DISTRIBUTION OF MAJOR ROCK UNITS AND LOCATIONS OF CERTAIN BERYL-BEARING PEGMATITES

In zoned pegmatites, beryl is commonly present in greater concentration in one or more zones than in others. In such pegmatites the distribution of the mineral must therefore be analyzed in terms of the zonal structure, and the value of estimates of grade and tonnage is dependent on the accuracy of the structural analysis. In this report, in accordance with the classification of pegmatite units developed by parties of the Geological Survey,[5] the outermost zone of a pegmatite is termed the border zone, the zone next inside is the wall zone, the innermost zone is the core. Any zones present between core and

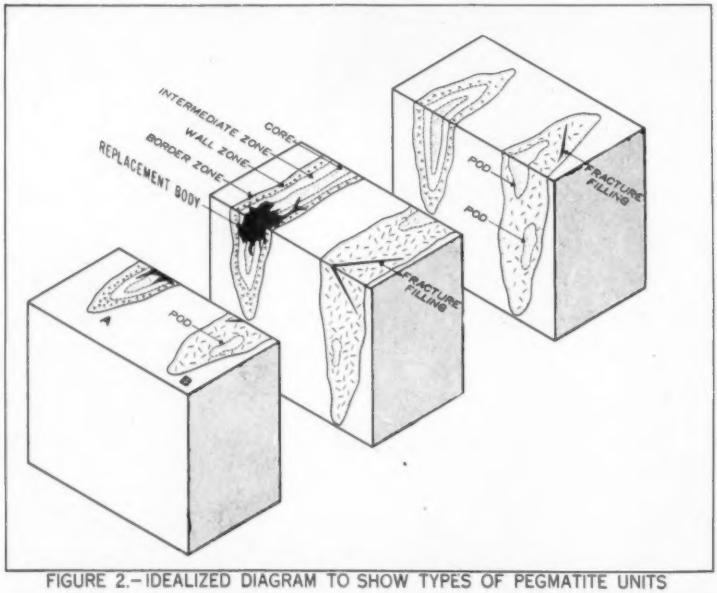


FIGURE 2.—IDEALIZED DIAGRAM TO SHOW TYPES OF PEGMATITE UNITS

wall zone are termed intermediate zones. Names such as "quartz-perthite pegmatite," given to units in legends of accompanying illustrations, indicate the dominant minerals of the units, but do not all express the full mineralogy of the units.

Many of the pegmatites examined contain pods, rudimentary zones that consist of coarse quartz, feldspars, micas, and other minerals in various proportions (Figs. 2-B and 5). The pods commonly are small, less than 20 feet by 10 feet in plan, and are sparsely scattered through material of finer grain that composes the bulk of a given pegmatite body. Some pegmatites contain tabular bodies that appear to be fillings of fractures in the pegmatites (Fig. 2-B). In still others, irregular bodies have formed by replacement of older lithologic and structural units, either along fractures or other structural elements, or along the boundaries between crystals.

[5] Cameron, E. N., Jahns, R. H., McNair, A. H., and Page, L. R., op. cit.

The beryl-bearing pegmatites consist essentially of perthite, plagioclase, (albite to albite-oligoclase so far as determined), and quartz, with subordinate to minor amounts of muscovite. Accessory minerals present in various pegmatites in addition to beryl include biotite, garnet, apatite, tourmaline, lepidolite, spodumene, monazite, columbite-tantalite, uraninite (and alteration products), fluorite, pyrite, sphalerite, and galena. There is a wide range in the ratio of perthite to plagioclase, and in bulk composition the bodies range accordingly from granitic to quartz-monzonitic. Some of the pegmatites in the Monson gneiss, such as the Case pegmatites, are perthite-rich, but plagioclase is abundant in most pegmatites in the Bolton schist and in some is the predominant feldspar. No definite correlation between beryl content and the plagioclase-perthite ratio has been established. In some of the pegmatites beryl is more closely associated with plagioclase than with perthite, in others it occurs chiefly with perthite, and in still others its distribution appears to be independent of the type of feldspar.

BERYL IN PEGMATITES IN CONNECTICUT.

Beryl in pegmatites in Connecticut is commonly green, blue green or yellow green, but rose, white, colorless, and yellow beryl are also found. Zoned crystals are not unusual. The crystals are commonly unaltered, and if free of adhering or intergrown feldspar, quartz, and other matrix minerals, may be expected to assay between 11 and 14 per cent BeO. In some deposits the beryl occurs in crystals that are free of impurities and break cleanly from the matrix. In others the crystals contain inclusions of feldspar or other minerals or, because they are in interlocking contact with matrix minerals, are separable by hand only with difficulty.

The crystals range from a hair's width to more than 1 foot in diameter, and from a quarter of an inch to more than 2 feet in length. Although the size range is broad, large beryl crystals are not abundant in the pegmatites in Connecticut, and this is particularly true of the deposits that contain the principal known and inferred amounts of beryl. The bulk of known Connecticut beryl is in crystals that are less than 4 inches long and less than an inch in diameter, and are too small to be separated by hand.

Beryl has been found in the majority of the pegmatites examined, but in most is rare or occurs as sparsely scattered crystals. Only 10 of the pegmatites examined average 0.2 per cent or more beryl, either throughout or in sizeable portions.

TYPES OF BERYL DEPOSITS.

Six structural types of beryl concentrations have been recognized thus far in Connecticut pegmatites; border-zone, wall-zone, intermediate-zone, pod, fracture-controlled, and disseminated deposits. As with mica deposits,[6] gradations between types are found. Examples of the various types are listed in Table I, and the locations of the pegmatites mentioned are shown in Fig. 1.

[6] Cameron, E. N., Larrabee, D. M., McNair, A. H., Page, J. J., Shainin, V. E., and Stewart, G. W., op. cit., p. 374.

TABLE I.

OCCURRENCE OF BERYL, GRADES, AND ESTIMATES OF TONNAGES—SELECTED BERYL-BEARING PEGMATITES OF THE MIDDLETOWN DISTRICT.

Pegmatite	Beryl content of pegmatite as indicated by crystal measurements							
	Occurrence of beryl	Parts of pegmatite covered by crystal measurements and tonnage estimates	Area of pegmatite exposures covered by crystal measurements (square inches)	No. of beryl crystals in exposures covered	Total area of beryl in exposures covered (square inches)	Per cent beryl in pegmatite	Estimated tonnage of pegmatite	Estimated tonnage of beryl
Case No. 1	Chiefly in border and wall zones	a. Full thickness	16,560	75	24.3	0.15[1]	2,000	3.0
		b. Border and wall zones	10,414	282	42.72	0.41		
Case No. 2	Border, wall and intermediate zones	a. Full thickness	33,136	104	114.18	0.34[1]	23,570	80.0
		Border, wall and intermediate zones	16,568	104	114.18	0.68		
Case No. 3	Chiefly in border and wall zones	Full thickness	35,881	325	79.82	0.22[1]	14,250	31.0
Slocum	Border, wall and inner intermediate zones	Full thickness	28,166	171	103.02	0.37	935+	3.5+
Bordonaro								
A. Northern and southern parts combined	Border, wall and intermediate zones	Full thickness	43,460	190	303.33	0.70	7,787[2]	40.0[2]
B. Southern part only	Border zone only	Full thickness	16,358	82	52.13	0.32		
Andrews	Chiefly in intermediate zone	a. Intermediate zone	96,926	82	508.68	0.52		Probably Small
		b. Remainder of pegmatite	16,718	26	18.20	0.11		
Consolidated No. 2	Chiefly in pods	a. Richest pod	6,211	36	59.26	0.95		Probably Small
		b. Remainder of pegmatite	51,912	6	3.27	0.006		
Selden (East Selden)	Disseminated but locally concentrated around pods	a. Full thickness	103,884	499	354.66	0.34	20,800+	70.0+
		b. Richest pod	35,053	297	268.08	0.76		
Consolidated No. 1	Disseminated but locally concentrated around pods	Full thickness	76,147	68	33.28	0.04	40,000+	16.0+
Hale-Walker	Disseminated	Full thickness	18,169	263	38.80	0.21	3,780+	7.9+
Gotta-Walden	Disseminated	Full thickness	96,176[3]	[3]	810.33[3]	0.84	71,563	601.0
Hollister—Pegmatite A[4]	Disseminated	Full thickness	20,580	80	18.70	0.09	7,200	6.5
Pegmatite B[4]	Disseminated	Full thickness	10,685	21	12.34	0.11		Small
Western	Disseminated but concentrated in pods and fracture-fillings	a. Pods and fracture-fillings	10,944	64	124.63	1.14	?	?
		b. Remainder of pegmatite	7,445	19	1.31	0.02	16,000+	?
							207,885+ Total	859+ Total

[1] Weighted average. [2] Tonnage estimate may err on conservative side.
[3] Counts partly by E. E. Maillot. Project Engineer, Bureau of Mines. Of the total beryl exposed, 313.03 sq. in. represents 107 crystals.
[4] Pegmatites A and B may be parts of a single body.

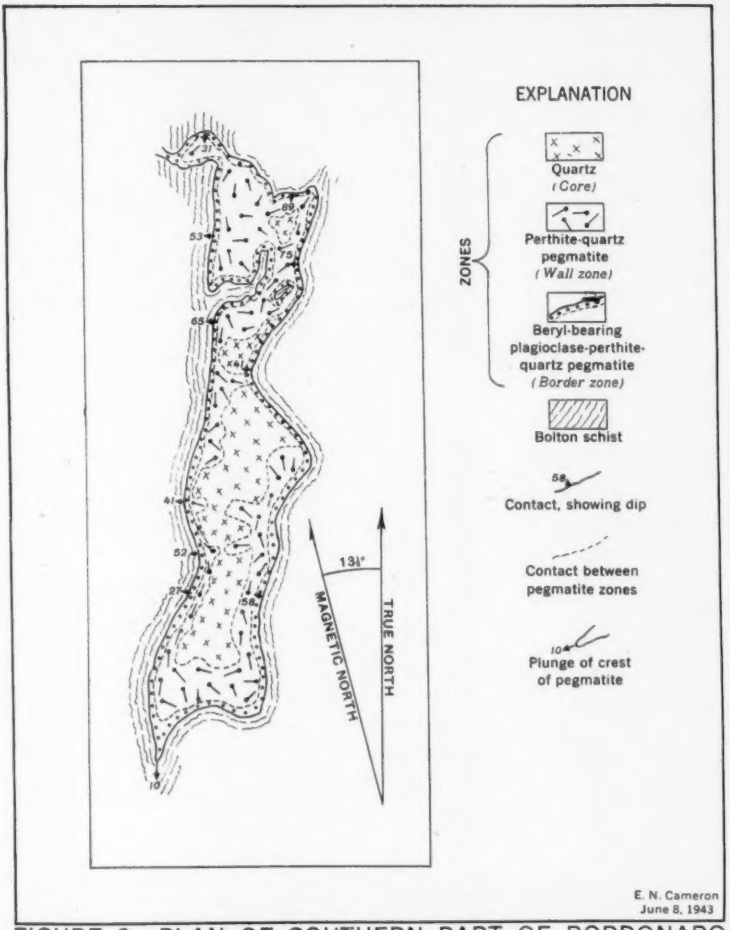


FIGURE 3.—PLAN OF SOUTHERN PART OF BORDONARO PEGMATITE, PORTLAND, CONNECTICUT

Border-zone and wall-zone deposits commonly occur together. In these, beryl is concentrated in the border zone, commonly a layer of fine-grained pegmatite a few inches or less in thickness, and in the wall zone, which is coarser grained and commonly a foot or more thick. Beryl occurs in the border zone in very small crystals and in most pegmatites is not sufficiently

[3] Counts partly by E. E. Maillot. Project Engineer, Bureau of Mines. Of the total beryl exposed, 91.6% is in deposits too small to be of economic importance.
[4] Pegmatites A and B may be parts of a single body.

abundant to enter significantly into tonnage estimates. The southern part of the Bordonaro pegmatite (Fig. 3), however, is an exception. The beryl content of this pegmatite as indicated by crystal measurements is 0.32 per cent, and the beryl occurs entirely in the border zone. In general, the beryl crystals in a wall zone are progressively coarser inward from the walls, and

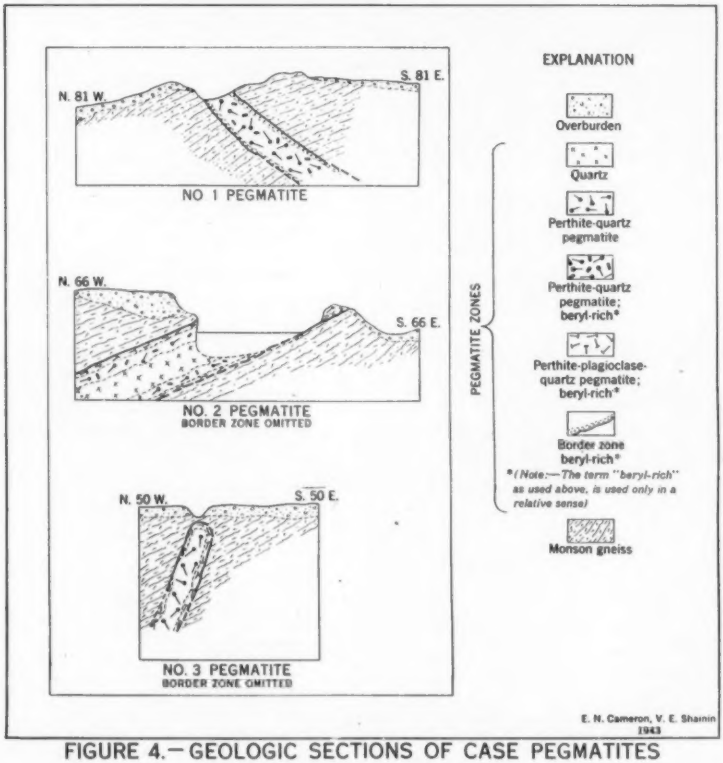


FIGURE 4.—GEOLOGIC SECTIONS OF CASE PEGMATITES

the larger crystals, ranging up to 1 foot in diameter and a foot or more long, can be separated easily by hand. The essential constituents of beryl-bearing wall zones are quartz, plagioclase, and perthite in various proportions. Perthite is dominant over plagioclase in the majority of the wall-zone deposits studied, but in some the beryl is more closely associated with plagioclase and quartz than with perthite. The Case No. 1 and the Case No. 3 pegmatites (Fig. 4) show deposits of the wall and border-zone types. In the Case No. 1 pegmatite (Fig. 4) beryl is concentrated in the border zone (Table

I) and the outer 18 inches of the quartz-perthite pegmatite next inside, especially along the footwall. Though not mapped separately, a wall zone relatively rich in beryl is therefore present.

In intermediate-zone deposits beryl is concentrated in one or more zones lying between the wall zone and the core. In the three deposits of this type so far found in Connecticut, the Case No. 2 pegmatite (Fig. 4), the northern part of the Bordonaro pegmatite, and the Slocum pegmatite, the intermediate zones are rich in potash feldspar (perthite). Beryl crystals observed in these deposits range from less than 1 inch to 10 inches in length, and up to 4 inches in diameter. The larger crystals form an appreciable part of the beryl content of the deposits and are recoverable by hand sorting. None of the deposits, however, can be shown at present to contain a large tonnage of beryl. Beryl is also present in the wall and border zones of the three pegmatites, but the cores are barren.

Pod deposits are found in some pegmatites in the Middletown district. In them beryl is concentrated in or adjacent to pods composed essentially of coarse quartz and perthite, with which various amounts of plagioclase, muscovite, and tourmaline may be present. The East Selden pegmatite (Fig. 5 and Table I) and the Western pegmatite (Table I) are examples. Beryl crystals observed in some of these deposits are large enough to be separated by hand, ranging up to at least 9 inches long and 6 inches in diameter, and the grades of some pod deposits are comparatively high. Unfortunately, most pods are small, less than 20 feet long and 10 feet in diameter, and are sparsely distributed through the pegmatites that contain them. Much barren or nearly barren pegmatite would have to be moved in order to recover any appreciable amount of beryl. Within a given pegmatite, moreover, pods differ in beryl content, and some are barren entirely.

In some pegmatites, fractures are occupied by tabular bodies consisting of quartz or of quartz and feldspar, with or without subordinate amounts of muscovite and other minerals. Concentrations of beryl in such fracture-fillings are apparently not common, but striking examples are found in the Western pegmatite. Bodies of this type are small, mostly less than 30 feet long and 2 feet or less thick.

In addition to the tabular bodies, there are irregular bodies formed by replacement of older pegmatite units along fractures. They grade into the simpler fracture-fillings. The most striking are replacement bodies in the Strickland-Cramer pegmatite which consist essentially of quartz and cleavelandite. In places the bodies contain medium to large crystals of green, blue, yellow, or rose beryl that are readily separable by hand. Locally the bodies are rich in beryl, but the total tonnage of beryl available in them is very small. Many of the beryl crystals contain cores or inclusions of cleavelandite which it is impractical to separate by hand.

A disseminated deposit is a pegmatite that has beryl crystals scattered through its full width without apparent system. The Hale-Walker and Hollister pegmatites are among the examples of this type. Such deposits are small and low in beryl content, and most of the beryl crystals are too small to be separated economically by hand. The pegmatites consist essentially of

quartz, plagioclase, perthite, and muscovite in various proportions. Beryl is most closely associated with quartz and plagioclase.

Certain pegmatites show combinations of the above types. Beryl is found, for example, in all parts of the East Selden pegmatite. It is concentrated,

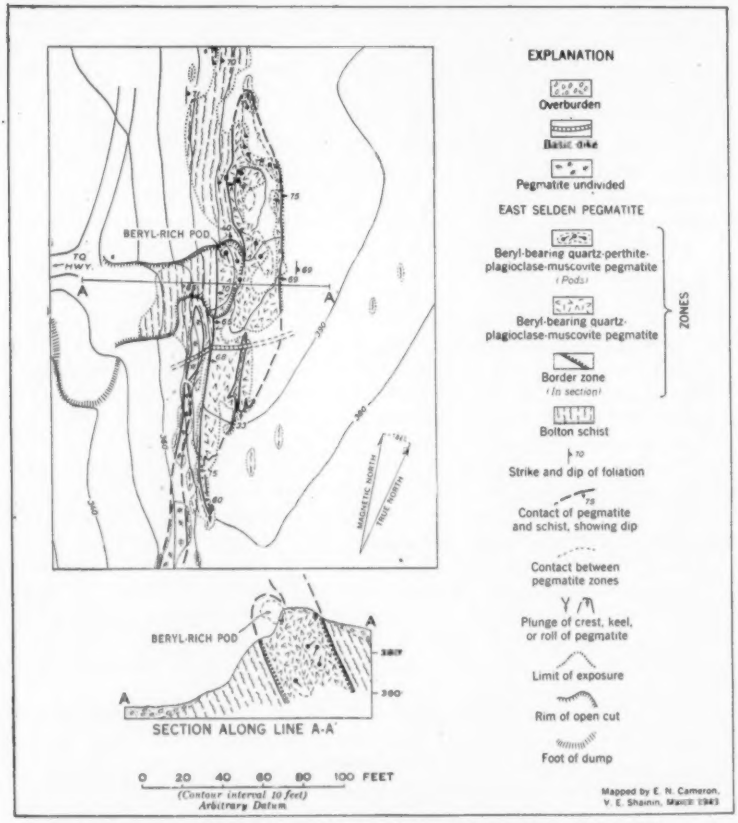


FIGURE 5.—MAP AND SECTION OF EAST SELDEN DEPOSIT. EAST HAMPTON, CONNECTICUT

however, adjacent to scattered pods of coarse quartz, perthite, plagioclase, and muscovite (Fig. 5), and locally in a zone along the walls that is too indistinct and discontinuous to be mapped. The Gotta-Walden pegmatite (Figs. 6 and 7) likewise shows a variety of beryl occurrences. This pegmatite has a strike length of at least 410 feet underground, a dip length of at least 370 feet, and an average thickness of about 8 feet. It is strikingly zoned,

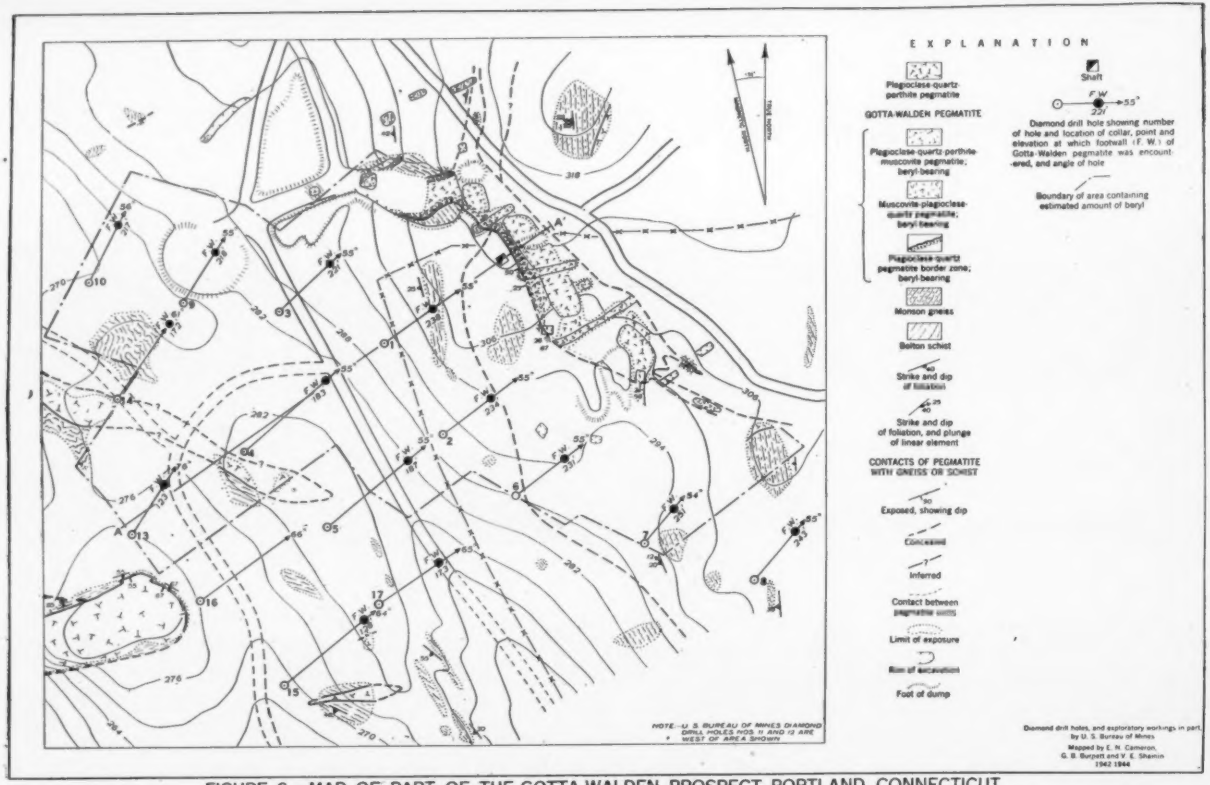

EXPLANATION
Plagioclase-quartz-perthite pegmatite
GOTTA-WALDEN PEGMATITE
Plagioclase-quartz-perthite-muscovite pegmatite; beryl-bearing
Muscovite-plagioclase-quartz pegmatite; beryl-bearing
Plagioclase-quartz pegmatite border zone; beryl-bearing
Monson gneiss
Bolton schist
Strike and dip of foliation
Strike and dip of foliation, and plunge of linear element
CONTACTS OF PEGMATITE WITH GNEISS OR SCHIST
Exposed, showing dip
Concealed
Inferred
Contact between pegmatite units
Limit of exposure
Rim of excavation
Foot of dump
Shaft
Diamond drill hole showing number of hole and location of collar, point and elevation at which footwall (F. W.) of Gotta-Walden pegmatite was encountered, and angle of hole
Boundary of area containing estimated amount of beryl
Diamond drill holes, and exploratory workings in part, by U. S. Bureau of Mines
Mapped by E. N. Cameron, G. B. Burpett and V. E. Shamin 1942 1944
NOTE.—U. S. BUREAU OF MINES DIAMOND DRILL HOLES NOS. 11 AND 12 ARE WEST OF AREA SHOWN
TRUE NORTH
MAGNETIC NORTH
0 50 100 150 FEET
Contour interval 5 feet
Datum is sea level

FIGURE 6.—MAP OF PART OF THE GOTTA-WALDEN PROSPECT, PORTLAND, CONNECTICUT

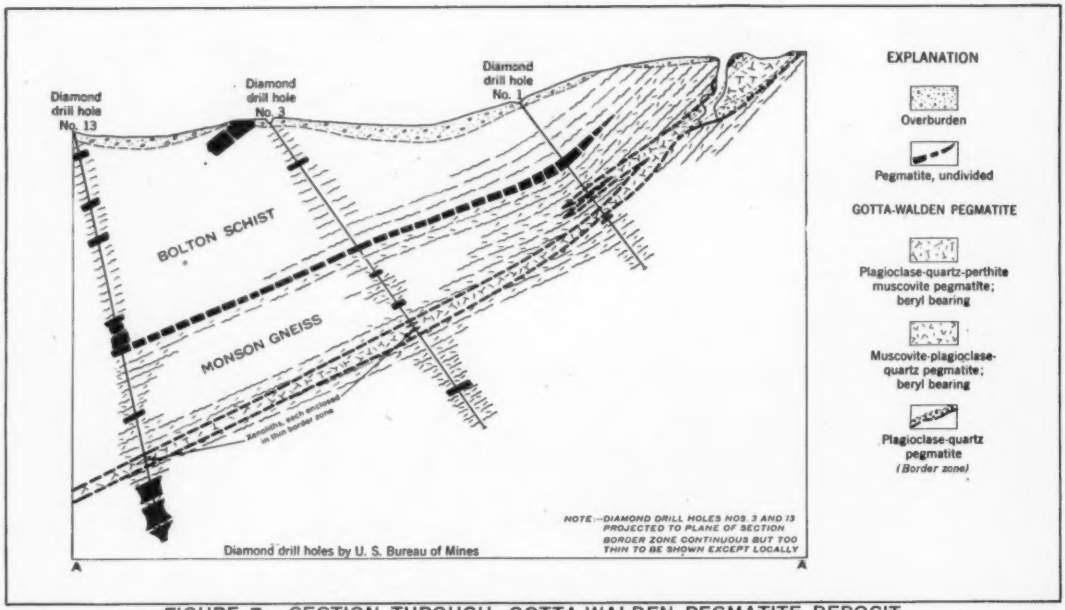

Diamond drill hole No. 13
Diamond drill hole No. 3
Diamond drill hole No. 1
BOLTON SCHIST
MONSON GNEISS
Xenoliths, each enclosed in thin border zone
Diamond drill holes by U. S. Bureau of Mines
A
A
NOTE.—DIAMOND DRILL HOLES NOS. 3 AND 13 PROJECTED TO PLANE OF SECTION
BORDER ZONE CONTINUOUS BUT TOO THIN TO BE SHOWN EXCEPT LOCALLY
EXPLANATION
Overburden
Pegmatite, undivided
GOTTA-WALDEN PEGMATITE
Plagioclase-quartz-perthite muscovite pegmatite; beryl bearing
Muscovite-plagioclase-quartz pegmatite; beryl bearing
Plagioclase-quartz pegmatite
(Border zone)

FIGURE 7.—SECTION THROUGH GOTTA-WALDEN PEGMATITE DEPOSIT

0 50 100 FEET

showing a fine-grained plagioclase-rich border zone, a muscovite-quartz-plagioclase wall zone rich in books of scrap mica along part of its hanging wall, and a core composed essentially of quartz, plagioclase, perthite, and muscovite. Beryl is most abundant in the border and wall zones but is also present in the core and in numerous partly digested xenoliths scattered through the pegmatite. This pegmatite was explored by the Bureau of Mines by means of trenches, pits, diamond drill holes, and a shaft. The pegmatite is of special interest because it contains the bulk of the beryl inferred on the basis of wartime investigations of pegmatites in Connecticut. The beryl occurs in crystals up to 11 by 16 inches, but most of the crystals are less than 1 inch in diameter and less than 3 inches in length. Attempts at hand sorting have shown that separation by this means is impractical, even under the maximum wartime price of $14.50 per short-ton unit (20 lbs.) of contained BeO for beryl concentrates of grade 8 to 12 per cent BeO, or the present price of $18.00 per short-ton unit. The Bureau of Mines is reported to have experimented with a flotation method for concentrating low-grade and finely disseminated beryl ores,[7] but the results of this work have not been released.

GRADES AND CHARACTERISTICS OF THE BERYL DEPOSITS.

Table I summarizes data on grades of some of the beryl-bearing pegmatites examined. It includes all pegmatites known to contain appreciable quantities of rock carrying 0.2 per cent or more of beryl. For each deposit the grade was determined by measuring the diameters of the area occupied by each beryl crystal exposed and computing the area occupied by each crystal. The sum of the areas of the individual beryl crystals gave the total area occupied by beryl crystals, and this divided by the total surface area of the exposures on which measurements were made was taken as the percentage of beryl by volume. As the specific gravities of pegmatite and beryl are approximately the same, the percentage by volume was taken as equivalent to the percentage by weight. In interpreting the measurements, consideration was given to the distribution of beryl within each pegmatite, and the degree to which the exposures give a true sample of the pegmatite. Where zones or other structural and lithologic units within a given pegmatite were unequally exposed, the measurements were weighted accordingly in computing the average beryl content of the pegmatite as a whole.

Grade determinations by this method are obviously not exact. Beryl too fine-grained to be recognized in exposures is not included in the measurements. Furthermore, few pegmatites are well enough exposed to permit fully representative measurements, and the roughness of most pegmatite exposures introduces unavoidable errors. Study of the pegmatites indicates that the amount of beryl too fine-grained to be visible to the eye is not sufficient to affect grade values significantly, but the other sources of error are more difficult to evaluate. It seems probable, however, that reasonably close approximations have been attained for the more fully exposed deposits. Counts of

[7] Jardine, F. M., Ore concentration and milling, Mining and Metallurgy, Vol. 26, pp. 63–65, 1945.

different but geologically comparable parts of a given deposit when matched against one another show satisfactory agreement. In most of the pegmatites or parts of the pegmatites covered by the counts, the beryl content is distributed among numerous small crystals. Sampling errors involved are therefore probably less serious than for pegmatites such as are known in other districts, in which the beryl occurs in sparsely scattered large crystals.

The beryl content of Connecticut pegmatites in general is low. Bodies of pegmatite or sizable zones or other pegmatite units that carry 0.2 per cent or more of beryl appear to be exceptional. Furthermore, in those deposits that appear to contain the largest tonnages of rock carrying 0.2 per cent or more of beryl, the beryl crystals on the average are so small that only a small fraction could be recovered readily by hand-sorting. Beryl large enough to be recovered readily by hand-sorting is most common in inner intermediate zones, replacement bodies, and pod deposits, and these have undoubtedly yielded the bulk of the production of the past. As these deposits are small, however, and have been struck only incidentally in the course of operations for feldspar and mica, the total production of beryl in Connecticut since beryllium entered the world market has likewise been small, probably in the neighborhood of 20 tons.

AMOUNTS OF BERYL PRESENT IN THE PEGMATITES.

Table I also gives estimates of the amounts of beryl that can be inferred with reasonable assurance to exist in certain of the deposits. Estimates for the Gotta-Walden pegmatite, the Case No. 1, No. 2, and No. 3 pegmatites, and the Bordonaro pegmatite are based in part on results of surface exploration and diamond-drilling done by the Federal Bureau of Mines in collaboration with the Federal Survey. Mr. E. E. Maillot was project engineer in charge for the Bureau.

From the practical standpoint, the significant figures for grade and tonnage for any one of the pegmatites listed are those given for the full thickness of the pegmatite. Though in a number of the deposits beryl is concentrated in one or more lithologic units, none of the pegmatites offers opportunity for selective mining of more than a small fraction of the beryl present.

The table indicates that the amount of beryl so far inferable for Connecticut deposits is not great. The amount is nearly as large as can be safely inferred at present for the remainder of New England, but in Connecticut deposits the percentage of beryl that is separable by hand is considerably lower than in certain pegmatites in New Hampshire and Maine. It is, therefore, not surprising that the bulk of the small output of New England has come from the latter two states.

Total amounts of beryl in Connecticut are undoubtedly much larger than those indicated in the table, for (1) additional beryl may exist in some of the deposits listed, in extensions that have not been blocked out by exploratory work, and (2) the present investigations have covered only parts of the Middletown pegmatite district. A narrow belt including and lying along the contact between the Monson gneiss and the Bolton schist, and extending

northward from the Hale-Walker prospect through the Gotta-Walden, Andrews, and Hollister pegmatites, appears to contain more pegmatites in which beryl is abundant than any other area examined in Connecticut. A large part of the section of this belt lying between the Hale-Walker pegmatite and the Andrews pegmatite has been examined by the writers, but the northward extension of the belt from the Andrews quarry to the village of South Glastonbury received little attention during the wartime investigations.

ECONOMIC OUTLOOK.

As the principal reserves of beryl in Connecticut are not economically recoverable by hand sorting, the present outlook for production is poor. Data on the cost of recovering beryl by flotation are not at hand, but barring prices for beryl considerably above those of the war period, it seems probable that a milling operation would have to be supported primarily by the yield of salable feldspar, scrap mica, and quartz. The operation would have to meet competition from operations in other pegmatites that would also yield these minerals and that are far more amenable to low-cost mining, owing to greater size, more favorable attitude, and/or higher content of feldspar. The Gotta-Walden pegmatite, which appears to carry the largest amounts of beryl, is thin and structurally unfavorable to low-cost mining. Its wall zone is rich in scrap mica, but drilling indicates that the zone nowhere extends as much as 100 feet down dip from the outcrop, and at the surface the zone is lacking in the southwest end of the pegmatite body.

The development and application of processes for milling beryl might be stimulated if prospecting should yield notable additions to the amounts of beryl inferred for the State. However, results of the present studies offer little hope that large deposits containing 0.2 per cent or more of beryl will be found, although it does seem likely that additional small deposits will be located.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
April 7, 1947.

STRUCTURAL CONTROL AND WALL-ROCK ALTERATION AT THE WILBERT MINE, DOME DISTRICT, BUTTE COUNTY, IDAHO.[1]

ALFRED L. ANDERSON.

ABSTRACT.

The ore at the Wilbert mine in Butte County, Idaho, consists largely of fine-grained galena deposited mainly by replacement of a dolomitic member in a thick series of complexly folded and faulted Ordovician quartzites. Ore has been mined almost continuously from the surface to a depth of 800 feet and laterally for a distance of about 2,000 feet. In the upper levels the ore bodies have been localized by fracture and breccia zones along the crest of a sharply bent, overturned anticline, in the intermediate levels by a fissure in the plane of a curved thrust fault, which lies on the underside of the overturned anticline, and in the lower levels by a weak zone of fracturing and slipping along the contact of dolomite with overlying quartzite. The fracturing along the contact has apparently been localized by a minor bend in otherwise uniformly dipping beds; the ore body extends laterally downward at first and then assumes a horizontal position in the deep part of the mine.

Mineralization was accompanied by marked alteration of the dolomite, which was feldspathized, carbonatized, silicified, and somewhat sericitized and pyritized prior to ore deposition. Feldspathization apparently was accomplished by high-temperature solutions emitted during a late stage of magmatic differentiation and was followed by intrusion of lamprophyre. Subsequent carbonatization and silicification (chiefly chalcedonization) apparently took place at relatively low temperatures.

The mineralization is probably related genetically to early Tertiary magma, and ore deposition apparently occurred at moderate depth under essentially telethermal conditions.

INTRODUCTION.

THE Wilbert is the largest and most active mine in the Dome district, which is one of several mining districts located on the flanks of the Lemhi Range in east-central Idaho. The mine is just within the northeast border of Butte County and lies mainly in Sec. 32, T.8N., R.24E., Boise meridian, about 40 miles from Arco, the county seat and nearest rail point (Fig. 1).

Ore was discovered about 1882, but there was no production until 1906. From then until 1931 the mine was in almost continuous operation and to 1929 inclusive, produced ore valued at about $2,000,000, which represented an output of 31,249,637 pounds of lead and 341,708 ounces of silver.[2] The mine was idle during the depression years of the 1930's, but was reopened in 1943.

[1] Presented at the Annual Meeting of the Society of Economic Geologists, New York City, March 21, 1947.

[2] Ross, C. P.: The Dome mining district, Butte County, Idaho, Idaho Bur. Mines and Geology Pamph. 39: p. 3 (1933).

The mineralization at the Wilbert mine has some interesting mineralogic aspects, but the most noteworthy features are those associated with changing structural controls and with wall-rock alteration. These features involve direction of the ore solutions first by one structural control and then another, utilizing fracture and breccia zones, fissures, and contact surfaces in com-

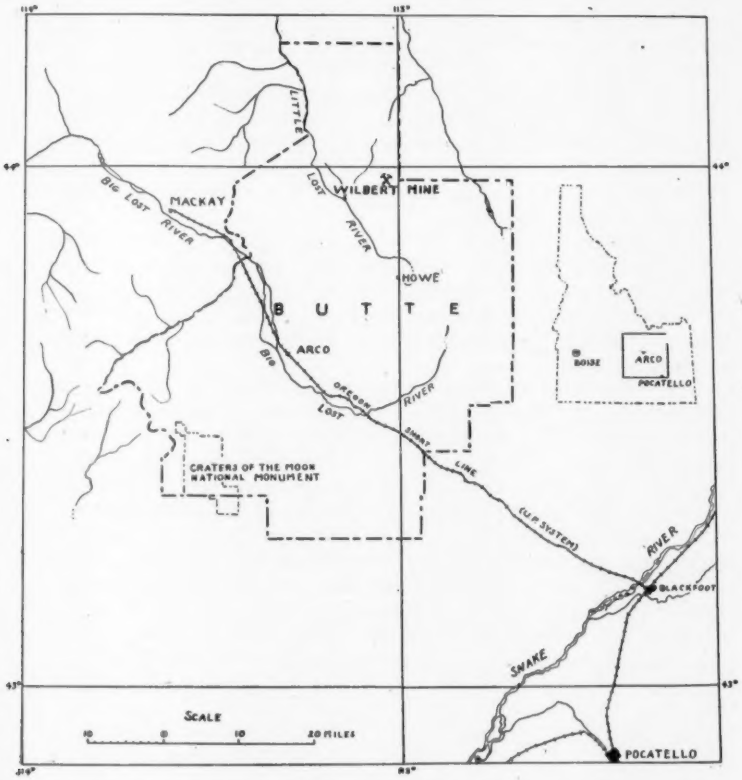


FIG. 1. Index map showing location of the Wilbert mine, Butte County, Idaho.

plexly folded and faulted rock, in every case with deposition of ore largely by replacement of dolomite. The wall-rock alteration involves the dolomitic rock and is represented by early, high-temperature feldspathization and by later, low-temperature carbonatization and silicification. The ore reflects deposition from low-temperature solutions of low thermal gradient associated with but rather remote from magmatic sources.

STRATIGRAPHIC SETTING.

The rocks at and in the vicinity of the Wilbert mine consist of a thick series of Ordovician strata of which the lower part is chiefly quartzitic and the upper part dolomitic.[3] The host for the ore bodies is a dolomitic member about 85 feet thick deep within the quartzitic series, and is overlain by about 1,000 feet of white, fine-grained quartzite (Upper white quartzite) and underlain by almost as much quartzite of more heterogeneous character. The rock immediately below the dolomitic member is a white quartzite about 65 feet thick (Lower white quartzite) which is not readily distinguishable from that which lies above. Beneath the lower white quartzite is first a purple quartzite about 400 feet thick, then a phyllitic shale member about 105 feet thick, and lastly a basal pebble quartzite at least 200 feet thick (measurements by Ross). These strata have been cut by a few small dikes exposed on different levels in the north end of the mine.

The important dolomitic member is composed of a dense, light-colored, fine-grained rock consisting of dolomite and quartz in varying proportions with scattered shreds of chlorite and locally crystals of feldspar.[4] Much of the rock is almost exclusively dolomite with a few scattered interlocked grains of quartz, but some is decidedly siliceous and may appropriately be classed as quartzitic dolomite.

The dikes include both silicic and basic varieties, but most of them have been so intensely altered, principally to carbonates and quartz, that their precise classification is not easy to determine. All of them are composed of porphyritic rock and those of silicic composition, though bleached and chalk-like, retain some remnants of the primary minerals. The principal basic dike is a lamprophyre enclosed within the ore zone in the far north end of the mine. The more central part of the lamprophyre has escaped alteration and is composed of a dark-gray, fine-grained rock whose porphyritic character is not so apparent as it is in the altered part where the phenocrysts have been replaced by pseudomorphous carbonates and silica. The fresh rock contains numerous small phenocrysts of olivine, augite, and biotite in a fine-grained groundmass composed of oligoclase and smaller amounts of biotite, augite, orthoclase, and magnetite. The rock is intermediate between kersantite and spessartite.

The age of the stratified rocks has been determined as Ordovician on fossil evidence.[5] The dikes appear to be pre-mineral, but as dike intrusion and mineralization are probably closely related events, their intrusion must have taken place in early Tertiary time, the date assigned the mineralization.

STRUCTURAL SETTING.

The bedded rocks have been intricately folded and faulted, being overturned and overthrust toward the northeast and offset by minor transverse normal or strike-slip faults. Two prominent overturned folds and closely

[3] Ross, C. P.: op. cit., p. 3.
[4] Ross, C. P.: op. cit., pp. 4–5.
[5] Ross, C. P.: op. cit., p. 3.

associated thrusts occur in the vicinity of the mine and one of the folds and faults has exerted a marked control on ore deposition. The folds are sharply bent (Fig. 4) and in part so overturned as to be nearly recumbent. The associated thrusts have considerable displacement; they have a fairly high angle but are curved and flatten and steepen considerably on the dip. This folding and faulting are believed to be a product of late Mesozoic orogeny.

The transverse faults are most conspicuous in the north end of the mine where they have caused appreciable offsets in the ore body. These faults strike about N.60° E. and dip steeply southeast. They apparently possess considerable lateral movement with shifting of the southeast side relatively to the southwest. One a short distance south of the present face appears to have a vertical throw of about 100 feet, but the actual displacement, because of lateral movement, is probably considerably less. Another fault of perhaps greater magnitude lies ahead of the present face. It is known from the relation of the rock masses on the surface in the canyon above the Wilbert camp and may introduce some complications in the search and development of ore. The post-mineral faults have the characteristics of the mid-Tertiary faults in the Birch Creek district a few miles to the east[6] and like them may have come into existence during Miocene deformation.

CHARACTER OF THE DEPOSIT.

The ore at the Wilbert mine is confined to the dolomitic member of the quartzitic series and is for the most part a replacement of the dolomite, subordinately a filling of fissure and breccia openings. The ore is valued chiefly for its lead but it also contains appreciable though relatively small amounts of silver, the ore produced having averaged about 18 per cent lead and 3 ounces of silver per ton. The ratio of silver to lead is much lower than in most of the lead ores of the region. Gold, copper, and zinc are also present, but the gold has averaged only 0.00024 ounce per ton and the ore has carried only 0.23 per cent copper. The zinc content is so low that it has not been reported in smelter returns.

Mineralogy.—The primary ore is composed almost exclusively of galena, but some of it contains meager amounts of sphalerite and pyrite, neither of which is generally visible except with the microscope. Unlike the galena in much of the region, that at the Wilbert mine is very fine-grained, individual grains measuring less than 2 millimeters in diameter. Its occurrence as "steel galena," however, is not the result of crushing or granulation but a feature of the original crystallization. These fine grains tend to be disseminated through the altered dolomite as small black specks producing what Umpleby[7] has called "pepper and salt ore," but it also forms massive aggregates in replacing dolomite along fractures or in filling openings in fractures and breccias. The pepper and salt ore, though not as high grade as the other, has been the source

[6] Anderson, A. L., and Wagner, W. R.: Lead-zinc-copper deposits of the Birch Creek district, Clark and Lemhi Counties, Idaho, Idaho Bureau of Mines and Geology Pamph. 70: p. 13 (1944).

[7] Umpleby, J. B.: Geology and ore deposits of the Mackay region, Idaho, U. S. Geol. Surv. Prof. Paper 97: 82–83, 116–117 (1917).

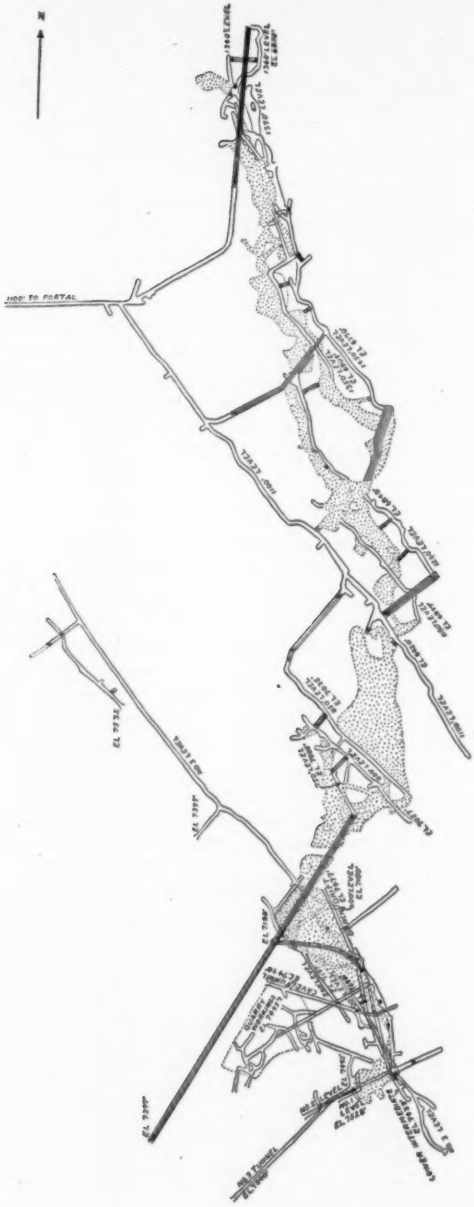


FIG. 2. Plan of underground workings at Wilbert mine showing stoped ground (stipled) and hence extent of ore.

of much of the mine production. The galena apparently is argentiferous, for no other mineral, which might contain silver, was observed. The sphalerite is of pale color and generally difficult to recognize, except in polished and thin sections, mainly as inclusion bodies within the galena. The pyrite is rarely visible in the massive galena, but in places appears as minute grains disseminated in the walls.

The gangue minerals are mostly those formed by hydrothermal alteration of the dolomite. They include minor amounts of feldspar, abundant calcite, dolomite, and chalcedony, a little quartz and sericite, and occasional grains of epidote, chlorite, and tourmaline.

ORE DISTRIBUTION.

Ore has been found almost continuously from the surface to a depth of 800 feet and laterally for a distance of about 2,000 feet (Figs. 2 and 3). The ore, however, has had a rather erratic distribution and has generally been confined to bodies of variable size and considerable irregularity. Some of the irregularity may be attributed to the replacement mode of ore deposition, but much of it is a reflection of the controlling structural conditions which change very markedly from upper to lower levels of the mine.

Upper Levels.—According to Umpleby [8] the ore bodies in the levels above the No. 3 were along the zone of sharpest bending in an overturned and considerably fractured anticline (Fig. 4), principally as a replacement of the dolomite, subordinately as a filling of fractures and breccias within the dolomite. The ore bodies were controlled largely by zones of faulting, but galena also penetrated little fractured or brecciated dolomite forming irregular bodies of pepper and salt ore. Such ore bodies were erratic in size and distribution, but were generally connected by stringers and controlled by general zones of fracturing. Ore shoots were elongated in the direction of fracturing and trended N.20°–30° W. and dipped either northeast or southwest at angles ranging from 20° to 80°. Some of the ore bodies between tunnels No. 2 and No. 3 were shown by Umpleby as notably flat (Fig. 4), composed largely of pepper and salt ore containing up to 20 per cent lead. Others, particularly along the lower intermediate level 55 feet above the No. 3, were reported to have contained thin lenses and stringers of ore forming ore bodies with 20 to 35 per cent lead.

Even though replacement was the dominant factor in mineralization, the fractures aided in directing the flow of mineralizing solutions and localized deposition sufficiently to produce ore bodies of commercial size. The immediate controlling fractures were apparently those formed during the development of the sharply bent, overturned fold, which broke and in part gave way to thrust faulting.

Intermediate Levels.—From the No. 3 to about the 600 level, the ore occurred as a vein between fairly well-defined walls in the plane of a curved thrust fault which lies on the underside of the fold and dips about 45°SW. (Fig. 4.). Some ore also was reported as a breccia cement of unaltered

[8] Op. cit., pp. 116–117.

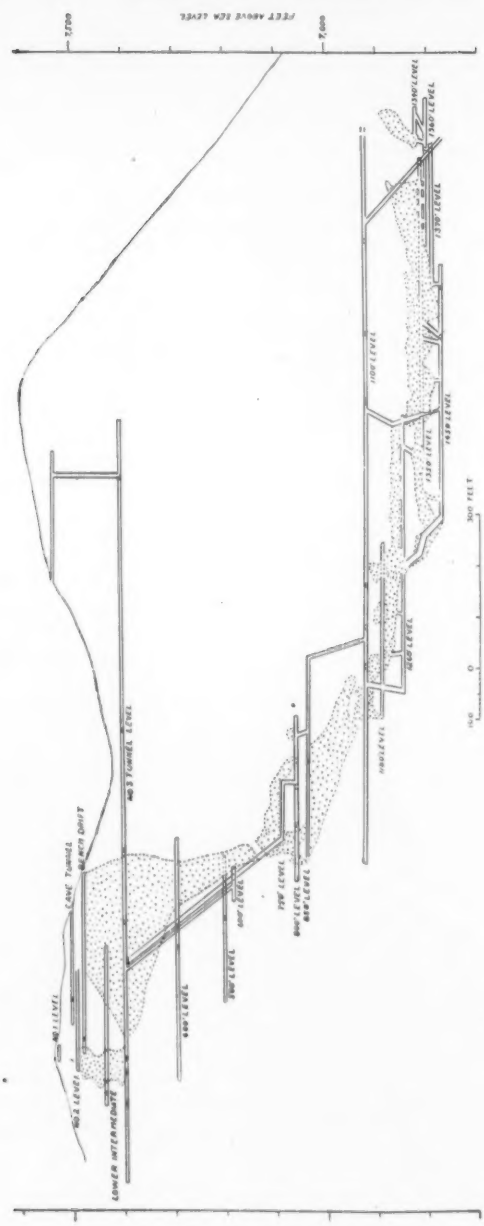


FIG. 3. Longitudinal section through the Wilbert mine showing position of ore shoot (section taken N. 40° W.).

quartzite. Along the No. 3 level the vein contained two ore shoots separated by about 75 feet of barren ground.[9] The vein apparently was stoped for more than 300 feet along the No. 3 level but the stope-length decreased with depth and near the 600-foot level was only about 40 feet long (Fig. 3).

Lower Levels.—From the 600 to the lowest levels of the mine the ore followed the contact between the dolomite and the upper white quartzite and occurred as a replacement of the dolomite (Fig. 4). The quartzite forms a

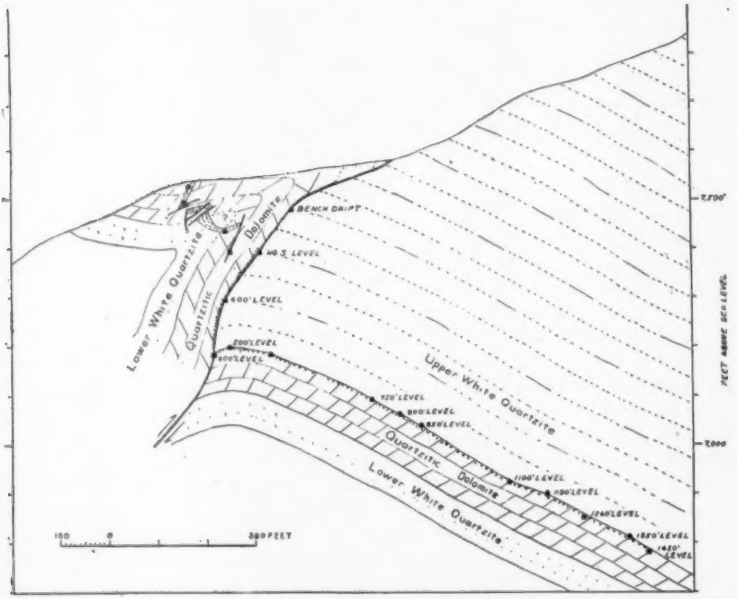


FIG. 4. Somewhat idealized cross section of the Wilbert mine showing structural relationships and localization of ore bodies (dotted).

fairly definite hanging wall but the ore within the dolomite shows an irregular distribution with the stope limits fixed by the grade of ore. Much of the ore apparently formed bodies well over 10 feet thick.

Instead of following the contact directly down the dip the ore extended downward laterally forming a somewhat pipe-shaped body that first plunged about 20° N. and then flattened and assumed a horizontal position parallel to the strike of the beds (Fig. 3). As the body flattened it tended to split and reunite but except for islands of little-mineralized rock, the ore formed a continuous body that has been stoped horizontally for a distance of 1,200 feet. In places the body approached the 1,450-foot level but in the present working the ore is above the 1,340-foot level. There the ore body appears

[9] Umpleby, J. B.: op. cit., p. 116.

to be ascending, apparently because post-mineral faulting had placed the ore previously stoped at a lower level. As in the upper workings some of the ore is the disseminated pepper and salt variety, but there is also considerable massive fine-grained galena in irregular bands and masses.

The distribution of the ore along the contact has apparently been controlled by minor fractures associated with a slight warp or bend in the northeasterly dipping beds. The formation of this minor undulation apparently was accompanied by some fracturing and slipping in the rock along and under the dolomite-quartzite contact, but no conspicuous faulting nor brecciation were involved. The fracturing, however, was sufficient to facilitate the intrusion of lamprophyric magma and to direct the flow of mineralizing solutions.

WALL-ROCK ALTERATION.

Alteration of the dolomite by the mineralizing solutions has not been particularly noticeable, except in the far north end of the mine, because the alteration products—calcite, dolomite, quartz, and chalcedony—are not greatly unlike the quartzitic dolomite itself. In the lower north end of the mine, however, the alteration has affected the lamprophyre within the ore zone and the "granitized" dolomite along side and has largely converted them to carbonates, quartz, and chalcedony with preservation of "igneous" rock textures. Thus the rock of the lower ore zone resembles a bleached, intensely altered porphyry, a part of which shows transition into the dark lamprophyre, a part into feldspathic dolomite with the appearance of a light-colored, somewhat pinkish porphyritic granite. The outline of the feldspars have been preserved in the altered rock accentuating its porphyritic character.

The alteration of the dolomite has been marked by progressive changes in which early feldspathization has played an appreciable role and later carbonatization, silicification, and locally sericitization and pyritization have played major roles. Some epidote and chlorite, and occasional microscopic crystals of tourmaline have also been formed in the altered rock, but their scanty distribution indicates that they are not products of essential alteration processes.

Feldspathization.—Except in the lower north end of the mine the feldspars are not conspicuous constituents of the dolomitic rock, but their presence has been mentioned by Ross [10] on the 1,450-foot level and also in the rock collected by Umpleby in the upper workings of the mine. At the present working face in the lower north end of the mine, the feldspars are so abundant that the dolomite of the ore zone resembles a porphyritic granite. Because of the subsequent alteration, however, only the outlines of the feldspars remain and the feldspar-impregnated rock is difficult to distinguish from the also altered lamprophyre, which intrudes it.

Some of the feldspars in the rock along the 1,450-foot level escaped alteration and have been identified by Ross [11] as sodic plagioclase and microcline

[10] Op. cit., p. 5.
[11] Op. cit., p. 5.

which are accompanied by a little interstitial chlorite, quartz, and bleached mica. In the dolomite collected by Umpleby in the upper workings and examined by Ross, the feldspar is plagioclase (approximately oligoclase-andesine). Accompanying it are small amounts of epidote and chlorite. Most of the feldspar in the rock at the present working face above the 1,340-foot level is so altered that it may be recognized as feldspar only by tabular outline, although occasionally a small remnant of clear feldspar may be found among the alteration products. The grains retain their outlines largely through pseudomorphous replacement by carbonates and silica.

Carbonatization.—The carbonates of lime and magnesia constitute the most abundant and widespread alteration products associated with the mineralization. The alteration has not only converted much of the feldspathized rock back to carbonates but has also produced changes within the original dolomite of the ore zone.

The carbonates include both calcite and dolomite. These occur together in variable proportions. In some of the leaner ore the carbonate seems to be largely dolomite similar to that of the original rock; elsewhere the carbonate is chiefly calcite, the calcite locally being three times as abundant as dolomite.[12]

These carbonates have not only replaced the feldspars in the dolomite pseudomorphously but they have also preserved the outlines of the phenocrysts and in part the groundmass textures of the lamprophyre. They have not, however, preserved the original dolomitic matrix of the feldspathized rock nor the texture of the unfeldspathized dolomite. The secondary carbonates have formed in somewhat larger grains.

Silicification.—The products of silicification are almost as abundant and widespread as those formed by carbonatization. They are most prominently manifested within the more central parts of the ore zone, but they may extend into the bordering rock and locally out along the bedding. The silicification was accomplished chiefly at the expense of the carbonates, which in the more intensely silicified zones were, except for the scattered remnants, virtually eliminated. The silica apparently pentrated the carbonate matrix with ease and also extended into the phenocrysts of the feldspathized rock, replacing the pseudomorphous carbonates and preserving the outlines of the original feldspars (Figs. 5, 6, 7, and 8).

The products of silicification include both chalcedony and quartz, but the quartz is much subordinate to the chalcedony and the dominant process of silicification has been chalcedonization. Much of the replacing chalcedony exhibits a tiny lathlike development, but some that entered openings is microspherulitic. The quartz forms small grains and granular aggregates which commonly are engulfed in the chalcedony (Fig. 6). In a few cases the quartz aggregates are pseudomorphous after the former feldspar crystals; but more commonly they enclose remnants of carbonate grains and are mantled by chalcedony, which completes the outline of the feldspar grain (Figs. 7 and 8). Most of the carbonatized feldspar crystals, however, have been completely or incompletely replaced by chalcedony alone.

[12] Ross, C. P.: op. cit., p. 10.

Sericitization.—Sericite is not an abundant nor conspicuous alteration product and its presence in the altered rock is evident only in thin sections of the ore. It is confined to small irregular patches and streaks in chalcedonized rock that has been impregnated with galena, some of its grains occurring as remnant inclusions or engulfed masses within the ore (Figs. 9 and 10). Its general restriction to ore-bearing zones indicates that its formation was closely associated with that of the ore. In comparison with the preceding stages of alteration the sericitization has been rather feeble.

Pyritization.—Pyrite is also a mineral of scanty distribution and is confined to minute, sparsely disseminated grains through the silicified rock and locally through the carbonatized rock beyond the areas of silicification. It is commonly more or less closely associated with the ore-forming stage though it is rarely a constituent of the more massive ore. Like the sericitization, the pyritization is an expression of the more feeble phase of wall-rock alteration.

Metallization.—Since so much ore occurs as grain impregnations in the carbonatized and chalcedonized dolomite, forming pepper and salt ore, its introduction might also be looked upon as a special phase of wall-rock alteration. The galena and sphalerite, which are the only observable sulphides other than pyrite, impregnate and replace all products of alteration including the carbonates, the silica, and the sericite (Figs. 9 and 10). The sphalerite and galena are invariably associated together, the sphalerite commonly as cores within the galena grains.

Accessory Processes.—Epidote, chlorite, and tourmaline are such minor constituents of the altered dolomite that they do not deserve recognition as products of significant alteration processes. The epidote was observed as occasional scattered microscopic grains as a replacement of the carbonates in the carbonatized lamprophyre and feldspathized dolomite in the lower, far north end of the mine. With chlorite it has been reported by Ross [13] in scanty amounts at higher levels. The tourmaline also was noted as occasional, widely scattered microscopic crystals in some of the pepper and salt ore in the lower workings, particularly in the chalcedonized rock impregnated by ore.

The formation of epidote apparently followed the carbonatization, but as its grains were not seen in contact with quartz or chalcedony, its position in the sequence cannot be determined exactly. Because of its distribution in the

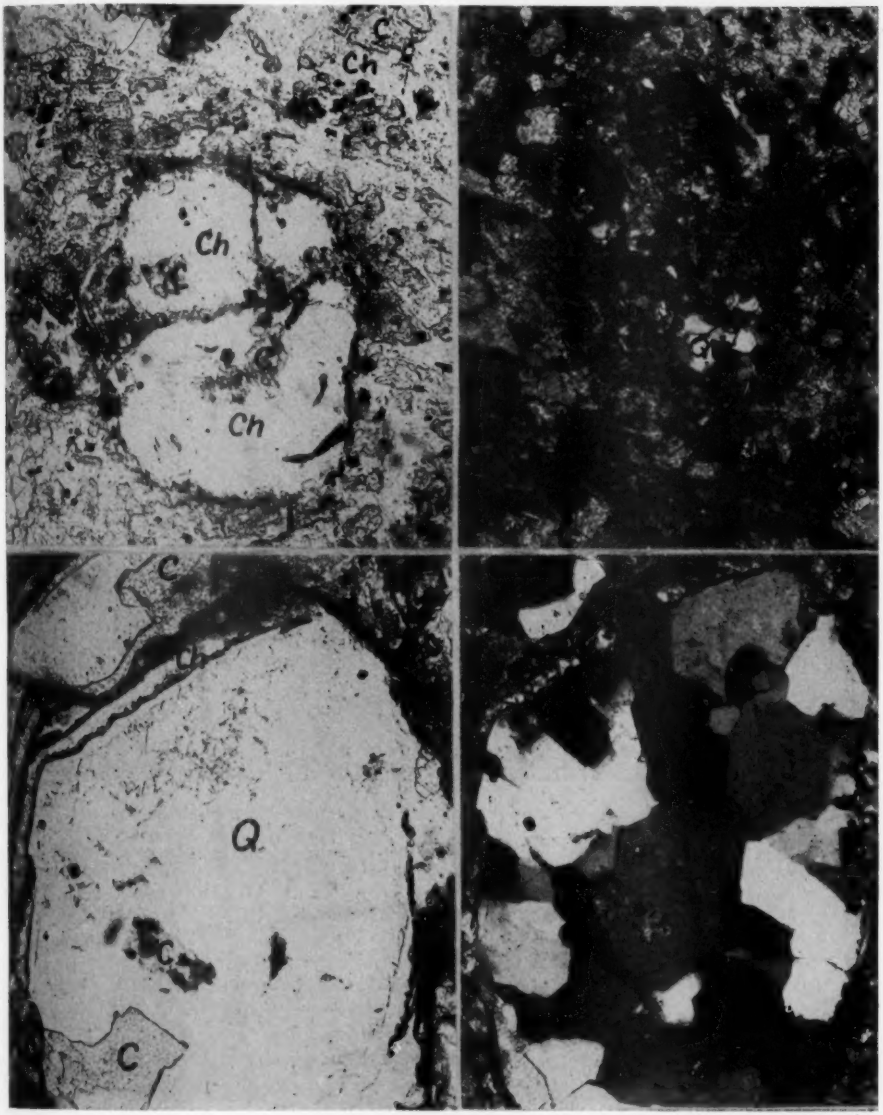
[13] Op. cit., p. 3.

FIG. 5, top left. Feldspathized dolomite subsequently carbonatized and silicified and then impregnated by minute crystals of galena (black). The outline of the feldspar has been preserved during subsequent alteration, but the interior is composed largely of chalcedony (Ch) with remnants of carbonates (C), which earlier had replaced the feldspar. The chalcedony has also permeated the carbonate matrix, the carbonates standing in relief above the chalcedony. Uncrossed nicols. × 42.

FIG. 6, top right. Same as Fig. 5 but with crossed nicols. A remnant of granular quartz (Q) is now revealed within the largely chalcedonized feldspar.

FIG. 7, lower left. Feldspar grain within altered dolomite almost completely replaced by quartz (Q), with retention of a little earlier carbonate (C). The grain also shows a narrow marginal zone of chalcedony (Ch) encroaching on the quartz but preserving the outer border of the feldspar. Uncrossed nicols. × 42.

FIG. 8, lower right. Same at Fig. 7 but with crossed nicols.



FIGS. 5–8.

chalcedonized rock the tourmaline may be later than the epidote and its formation may have taken place at or near the close of silicification.

CHARACTER OF THE SOLUTIONS.

Composition.—The abrupt change from feldspathization of the dolomite to carbonatization and silicification indicates a marked change in the composition of the mineralizing solutions and perhaps also a considerable time interval between "granitization" and the alteration more closely associated with the metallization. During the early stage of alteration the solutions apparently

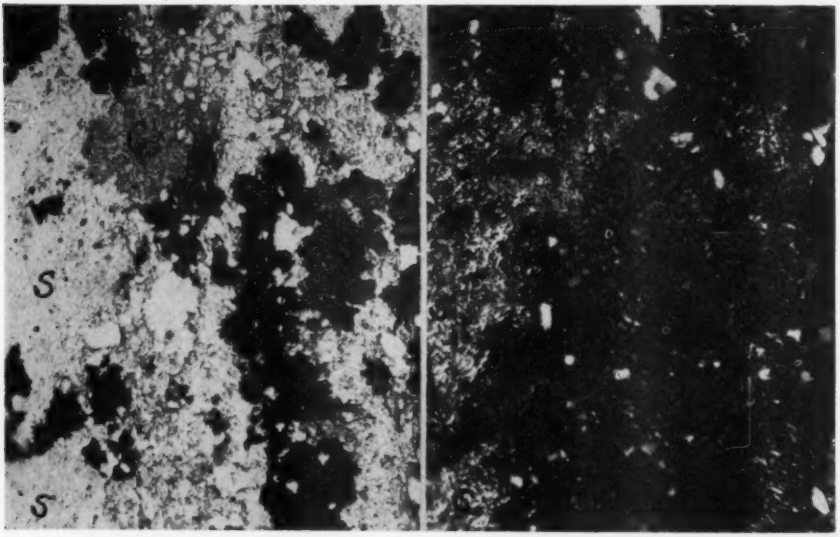


FIG. 9, left. Pepper and salt ore (black) impregnating and replacing the largely chalcedonized dolomite which has also been somewhat sericitized (S). A remnant of the carbonatized dolomite (C) remains. The chalcedony, some grains of quartz, and sericite are not easily distinguished individually except with crossed nicols. Uncrossed nicols. × 42.

FIG. 10, right. Same as Fig. 9 but with crossed nicols. The sericite appears as areas of light-colored mottling (S).

contained a notable concentration of alkalies, alumina, and silica; and the temperature and other conditions were such that the quartzitic dolomite became more or less widely impregnated with variable amounts of sodic plagioclase and potassic feldspar and locally with some chlorite, epidote, and quartz.[14] Thus the altered dolomite was made to resemble a porphyritic igneous rock. Alteration then apparently was interrupted by intrusion of

[14] Ross, C. P.: op. cit., p. 5.

lamprophyric magma and when alteration was resumed later the solutions had a very different composition.

At the start the later solutions were enriched in the carbonate radical and carried abundant lime and magnesia, a part but certainly not all of which may have been obtained from the dolomitic rock at deeper levels. Strongly contrasted chemically with the feldspar-containing rock and the lamprophyre, these solutions caused extensive formation of carbonates and virtual destruction of the feldspathized dolomite and much of the lamprophyric rock, producing changes even in the original dolomite itself. As the flow continued the solutions became highly silicic and caused widespread formation of chalcedony and subordinate quartz. At the start the silica-enriched solutions may have carried a little iron and possibly other constituents that went into the formation of the scantily distributed epidote and chlorite, which replace the carbonates. As the flow continued through the silicification stage, the solutions brought in a little boron and other elements that entered into tourmaline, later becoming somewhat enriched in potash with formation of sericite. The solutions then carried in iron and sulphur and the several ore constituents. The ore solutions were notably low in all metals except lead and silver and carried much less silver than is general for most of the lead deposits in the state.

Temperature.—The abrupt change from feldspathization to carbonatization indicates a marked drop in the temperature of the solutions between the early and later stages of alteration. The formation of feldspars suggests that the early solutions possessed a high degree of heat; the formation of carbonates and silica, that the later solutions had a relatively low degree of heat. The generally low temperature of the later solutions is also reflected in the texture and low precious-metal content of the ore, which prompted Ross [15] to regard the deposit, like the low-temperature ore deposited at the outskirts of the Leadville, Tintic, and Ouray mining districts, as formed remote from its magmatic source. The contrast in temperature between the early and later solutions may reflect the considerable lapse of time between feldspathization and carbonatization and may be dependent on changing conditions at the magmatic source. The early feldspathization apparently has a less close association with the mineralization than the later processes of alteration.

Source of Solutions.—Ross [16] was bothered by the lack of resemblance of the deposit at the Wilbert mine to any of the deposits of known Mesozoic or Miocene age in Idaho; but assuming the dike intrusions to be Tertiary he considered the mineralization also to be Tertiary and hence Miocene, the only Tertiary epoch in which he believed mineralization has occurred. The writer concurs in regarding the mineralization as Tertiary; but as the ore bodies have been offset by faults believed to have been formed during the mid-Tertiary crustal disturbance, the source of the solutions must have been early Tertiary magma in existence during the closing stages of the Laramide orogeny, the time at which probably all of the pre-Miocene deposits in the state came into being.[17]

[15] Op. cit., p. 12.
[16] Op. cit., p. 11.
[17] Reasons for the early Tertiary age of the older group of deposits formerly regarded as Mesozoic and related to the Idaho batholith are to be presented in papers now in preparation.

SUMMARY AND CONCLUSIONS.

The mineralization at the Wilbert mine is noteworthy in several respects: (1) the almost continuous persistence of the replacement ore bodies in dolomite over a considerable vertical and a relatively great horizontal distance; (2) the adjustment of the mineralization and ore deposition to changing structural controls; (3) the early "granitization" of the dolomitic wall-rock; (4) the subsequent carbonatization and silicification of the wall-rock; (5) the general dearth of metals except lead and a little silver; and (6) the fine grain of the galena. Of these features the relation of the ore to changing structural conditions and the wall-rock alteration stand foremost.

Ore deposition has been influenced very greatly by rock character and all the ore found so far has been in the dolomitic member of the thick Ordovician quartzites, mainly as a replacement of the dolomite, subordinately as a filling in fissure openings and breccias. Although the dolomite is the localizer, the distribution of the ore within the dolomite has depended on various fractures which served to direct the flow of the mineralizing solutions. As the dolomite has been folded and faulted, the structural controls are varied and complex and range from fractures and breccia zones developed along the crest of the sharply bent, overturned anticlinal fold in the upper part of the mine to a curved thrust fault on the intermediate levels and an almost flat zone of rock fracturing and slipping along a minor bend on the dip of the beds on the lower levels. The ore shifting from one control to another almost without interruption has formed bodies of erratic shape, size, and distribution, reflecting always the changing structural controls.

The mineralizing solutions, probably derived from a rather deepseated early Tertiary magma, were directed upward along some as yet unknown channel, very likely a deepseated zone of shearing or fracturing, and gained entrance either directly or indirectly into the flat to gently inclined permeable zone determined by fracturing and slippage along the contact of the dolomite with the overlying white quartzite. These solutions moved laterally in a southerly direction for a distance known to exceed 1,100 feet and then laterally upward for another 500 feet. When the solutions reached the curved thrust fault, they were directed upward along it for several hundred feet, changing the upward direction of flow from southwest to northeast. In about 200 feet, however, the solutions moved from the fissure within the curved thrust fault into the various fracture and breccia zones along the crest of the overturned anticline and left many bodies of ore generally connected by stringers. Thus the solutions followed a most devious course in their journey to the surface and left ore almost continuously from the present working face to the present surface.

As the solutions first reached the levels at which ore has been found they apparently had a high temperature and an alkalic composition. They caused some "granitization" of the dolomite by impregnating it with grains of sodic plagioclase and potash feldspar and locally with a little quartz and mica. These solutions were probably closely related to the pegmatitic stage of differentiation and thus represented residual magmatic solutions of hydrothermal

character emitted in advance of the ore-bearing solutions, even in advance of the lamprophyric magma, which was directed upward along the same zone of structural weakness. Apparently the constitution and temperature of the solutions were such as to yield the feldspars rather than the silicates and alumino-silicates of lime and magnesia of higher heats of formation.

When the solutions resumed their flow after intrusion of the lamprophyric magma, they had undergone a marked change in temperature and composition. The temperature had dropped to moderate or low levels and the solutions were enriched in the carbonate radical and in lime and magnesia. These solutions attacked the previously altered as well as the fresh dolomite and the lamprophyre and converted them in large part to calcite and dolomite. As the carbonatization ended the solutions became highly silicic and introduced large quantities of chalcedony and a little quartz into the altered rock. The solutions then became somewhat enriched in potash and added minor amounts of sericite to the silicified rock. Iron and sulphur were carried in and impregnated the altered rock with widely disseminated grains of pyrite. The pyritization inaugurated the stage of ore deposition, for thereafter the solutions deposited argentiferous galena, which makes up the bulk of the ore. Although the temperature of the solutions was probably moderate during the carbonatization, it was probably low during chalcedonization and, from the size of the ore minerals, it must have remained low during the time ore was deposited.

Except for the local increased feldspathization at the lower, far north end of the mine, there has been no apparent change in the character of the mineralization from the highest to the lowest levels. As the feldspathization has not been so closely associated with the ore-forming stage as the carbonatization, chalcedonization, and sericitization, it may be ignored in an evaluation of thermal controls attending ore deposition. Thus the deposit appears to reflect a low thermal gradient as well as deposition from solutions of low thermal character. Consequently, the ore may be expected to persist to greater depths or at least to the channel from which the solutions gained access to the present observable controlling structures. Just where the structural conditions that control the mineralization in the lower levels of the mine will change cannot be foretold. The safest guide to ore is the altered dolomite and the lamprophyre.

The deposit does not have the earmark of one formed at particularly shallow depths but on the contrary the textural and structural characteristics of the ore and the general structural controls indicate deposition at fairly moderate depths. The deposit differs from the more usual mesothermal deposit as well as from the more typical epithermal deposits by reason of its low thermal character. The mineralization may verge on the telethermal as proposed by Graton.[18]

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[18] Graton, L. C.: The depth zones in ore deposition, ECON. GEOL. 28: 547–551 (1933).

METASOMATIC PROCESSES.

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ABSTRACT.

The physico-chemical processes of transport and reaction, acting in metasomatism, are described in relation to the available size of opening, from supercapillary to intra-lattice. For complete, fine-grained replacement, a large proportion of the replacement must be accomplished in the openings of smallest size, by the processes operative in that type of openings. On the other hand, movement of matter for relatively long distances, must be accomplished in larger openings. Each of the described mechanisms may take part in some phase of the overall process of metasomatism. Some recently postulated processes are found to be unsatisfactory as stated.

GEOLOGICAL literature suggests the need of a classification of the physico-chemical processes that may be active in metasomatism. Therefore, the following analysis of these processes is submitted. A consideration within this outline, of some processes that have been postulated, will show that some are not fundamentally new, and that others are not precisely defined. Such considerations may contribute to economy of thought and experiment.

PROCESSES OF TRANSPORT AND REACTION.

At the outset, a distinction that might be made among the various processes is that between "transport" and "reaction." That is, there is the problem of getting the replacing material *to* the replacement front (and, concurrently, getting the replaced material away from it), and also, the problem of an exchange of material *at* the replacement front. As will be evident in the discussion below, this distinction, in some cases, will not be a definite one as the site of replacement is closely approached. However, as a tentative classification, let us consider the various processes in the light of a fundamental physical factor, one which will determine, to a certain extent, which process will be most active—*the size of opening* available for transport of material. This is an extension of the classification of Van Hise.[1] Of course in most cases, especially where a large volume of material is being replaced, the material must have moved close to the replacement front through rather large openings, and any particular particle may have run the whole gamut of opening sizes before finally reaching its resting place.[2] In addition, it should be stated that exchange of material may take place along the boundaries of any of the various size openings, although in the larger openings this factor

[1] Van Hise, C. R.: Treatise on metamorphism, U. S. Geol. Surv., Mon. 47: 134–146 (1904).
[2] Bateman, A. M.: Economic Mineral Deposits, Wiley, New York, pp. 95–96 (1942).

is probably not important, if the arbitrary distinction between metasomatism and cavity filling is made at a convenient point.

The sizes of openings to be considered are categorized at follows:

(1) Supercapillary.
(2) Capillary.
(3) Grain boundary.
(4) Intra-lattice.

Supercapillary Openings.

Transport.—In this most obvious of cases, movement of liquids and gases is relatively unrestricted, with either streamline or turbulent flow, according to the governing conditions (velocity and opening size). The movement of originally solid matter may be accomplished either in solution or in a dispersed state (that is, particles of colloidal or larger size). It is probable that a large volume of the replacing material is moved through openings of this category, such as fissures and large pore spaces, to a point near to the replacing front.

Reaction.—There is opportunity, of course, for solutions to dissolve, peptize, or mechanically disintegrate the walls of such openings; and later to precipitate, adsorb, or settle material into the spaces left by the removal. Without recourse to channelways of a smaller size, however, such replacement must proceed in a gross manner, large amounts of matter being removed before any replacing matter is deposited ("mold" pseudomoryhs, or similar cavity fillings); or, it must be of very small extent (a monomlecular alteration layer, for example). I assume that most geologists would not regard the gross filling of a large solution cavity as a type of metasomatism; but as the size is reduced until extremely small particles, or even molecules, are being exchanged, the distinction between cavity filling and metasomatism must be made at some arbitrary size. If we assume, for convenience, that metasomatism involves the exchange of matter of the size of colloidal particles or smaller, then, if the metasomatism is to affect any large proportion of the original volume, there must be access to all parts of the volume, through smaller openings.[3] Admittedly this assumed limiting size is small, if one considers the macroscopic imperfection with which many deposits (called replacements) reproduce previous structures.

[3] Simple geometrical considerations will show that the percentage replacement (percent of total volume that consists of replaced material at the end of the process),

$$R = a \cdot P \cdot \frac{A_p}{V_p} \cdot 100$$

where "a" is the diameter of largest replacement unit under consideration, "P" is the porosity of the replaced body (considering only pores "a" or larger), and A_p and V_p are the area and volume of such pores. For example, consider cylindrical pores, where

$$\frac{A_p}{V_p} = \frac{4}{d},$$

"d" being the diameter of the pores. The *maximum* porosity for a set of cylinders is 0.91 (with hexagonal packing), so that

$$R = 364 \cdot \frac{a}{d}.$$

Of course other geometrical arrangements are possible, and the relation is not accurate as "d" approaches "a" in size; but it is obvious from the above relation, that metasomatic exchange of matter will be negligible where openings are not smaller than supercapillary in size. Their importance for transport of metasomatic materials and products, however, is paramount.

Capillary Openings.

As openings become so constricted that the force fields of the walls begin to have an appreciable effect in relation to intermolecular forces of the fluid, a different set of processes become dominant.

Transport.—A. Fluids. The movement of fluids continues, but almost entirely by *streamline flow,* and in accordance with Poisseuille's equation. It should be noted, that for gases moving under low pressures and through very small openings (mean free path greater than five times the diameter, in the case of a cylinder), flow may take place in an easier manner by *"molecular streaming,"* and in accordance with Knudsen's equation.[4] However, the conditions under which this mechanism operates may represent a transition between capillary and "grain boundary" conditions. Movement of liquids may take place, to a certain extent, without an external pressure differential, by *capillarity.* But after capillarity has reached its maximum vertical height, movement of this type may continue only if liquid is removed from the top (as by evaporation).

B. Solids, by fluid transportation.—The movement of originally solid matter may take place through capillary openings, in solution or colloidal dispersion, by either flow of the fluid or by diffusion through the fluid. The flow of solutions has been assumed by some writers to be equivalent to the flow of any other fluid,[5] but the experiments of Duffell indicate that this assumption may require modification.[6] The following analysis of his experiments leads to the conclusion that:

(*a*) The solvent-transportation of *some* ions, through capillary openings in *rocks,* is *slowed* by adsorption or chemical reaction with the walls. Such an effect will be partially balanced by diffusion of the ions, down the concentration gradient so produced.

(*b*) Where flow of the solvent is entirely due to capillarity, solvent-transportation of the ions *may* be inappreciable; in this case the ions will move entirely by diffusion through the solvent.

In measuring the rate of movement of solutions, by capillarity, through pore spaces of rocks, Duffell noted that the metallic ions of the solvent lagged behind the solvent. As a matter of fact, these ions moved at the same rate as they would diffuse through an already saturated rock. This means, as pointed out by Duffell, that the solute penetrates the rock by *diffusion* through the liquid phase that has already filled the pore spaces ahead of it. The causes of this particular separation have a further significance not considered by the author. He postulated [7] four possible causes: a difference in rate of migration of acidic and basic portions of the solution, chemical reaction with the walls, adsorption on the walls, and filtration by the rock (as a semi-permeable membrane). As to the first possible cause, migration, relative to the solvent,

[4] Knudsen, M.: Die Gesetze der Molekular-strömung und der inneren Reibungströmung der Gase durch Röhren, Ann. Phys. 28: 75–80 (1909).

[5] Boydell, H. C.: The role of colloidal solutions in the formation of mineral deposits, Inst. Min. Met. Trans. 34: 84–85 (1937).

[6] Duffell, Stanley: Diffusion and its relation to ore deposition, Econ. Geol. 32: 494–510 (1937).

[7] Op. cit., pp. 506–507.

is unnecessary, for the solute to keep up with the solvent, if it is uniformly in solution. In regard to the last-named cause, mechanical separation of ordinary ions by a membrane of small pore size is not possible. Lindgren, cited in corroboration by the author, actually refers to the separation of ions from colloidal particles.[8] The separation must, in actual fact, be due to either adsorption or chemical reaction. This means, then, not only that the movement of the ions through the capillary spaces is taking place by diffusion, but that the rate of diffusion is being controlled by an inter-face process. Furthermore, a little consideration will show that this control may well be quite variable with time: if the process is a chemical reaction, the products of this reaction will eventually make unaltered rock difficult of access to the solution; if the process is adsorption, it will soon reach equilibrium, and the process will then slow down and stop. The extent to which capillary openings of rocks may limit the movement of solutes to what is virtually a process of diffusion, was determined only for the very slow velocities of flow caused by capillary action, and the effect upon the negative ions was not determined.

The results obtained by Duffell with colloids are equally important. The common inorganic or organic colloids tried by Duffell penetrate the pore spaces of the rock to a negligible distance, either by flow or by diffusion. This is either because of adsorption, or because of precipation by electrolytes dissolved from the rocks; for while "ultrafiltration" or "dialysis" of colloids is possible with certain very fine membranes, it seems unlikely that the specimens used did not have any openings larger than ordinary colloidal particles (two microns). The fact that, because of the combined effects of size and adsorption, many colloids may be separated in the laboratary by semi-permeable membranes through which one will move and another will not, indicates that capillaries are by no means always inpenetrable to colloids. It would be expected that some colloids would be stopped by the pore spaces of rocks, which may contain appreciable concentrations of electrolytes, as was found by Duffell.

C. Solids, by diffusion.—Diffusion of ions or molecules through a fluid phase, as a process leading to mineral deposition, has been discussed by a number of authors.[9] In general, diffusion of an ion in a fluid of infinite extent will take place according to Fick's equation, in proportion to the concentration gradient and the diffusion coefficient of that ion, which in turn will be dependent on temperature and concentration. In pore spaces such diffusion will take place through the whole volume of solute represented by *available porosity*, with the probable exception of a tightly adsorbed mono-layer of solute along the walls. Diffusion in capillary openings will take place at a

[8] Lindgren, W.: Mineral Deposits, p. 196, McGraw-Hill, New York, 1928.

[9] Boydell, H. C.: The role of colloidal solutions in the formation of mineral deposits, Inst. Min. Met. Trans. 34: 85–98 (1924). Gay, R.: Etude des phénomènes de la précipitation par une méthode de diffusion, Soc. Fr. Min. Bull. 68: 60–149 (1945). Korzhinsky, D. S.: Mobility and inertness of components in metasomatosis, Acad. Sci. U. R. S. S. Bull. (7), Cl. Sci. Math., Ser. Geol. 1: 58–60 (1936). Liesegang, R. E.: Geologische diffusionen, Steinkopf, Dresden (1913). Watanabe, M.: Some problems of diffusion in the special reference to the study of ore deposits, Tohuku Imp. Univ. (Sendai) Sci. Rpts. (3) 2: 105–185 (1924). Whitman, A. R.: Diffusion in ore genesis, ECON. GEOL. 23: 473–488, 928–929 (1928); 24: 330–335 (1929).

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slower rate than in free solution,[10] and the effect of the capillaries will increase with concentration. An electric force field will greatly affect the diffusion of ions or other charged particles; the modified diffusion equations for ions have been derived by Gay.[11] Chemical reactions will also affect the rate of diffusion; for example, the effect of precipitation on the diffusion equation has been calculated by Watanabe.[12] Most important of all, either of these effects may bring the diffusion process entirely to a stop, placing a limiting distance on the action of the processes; which may lead to contemporaneously formed banded structures in mineral deposits.[13]

Diffusion of a colloidal disperse phase is also possible, although the same restrictions, as to size and tendency to be adsorbed, must still be considered. Because or their larger size, colloidal particles have a much lower mobility than ions or molecules, and hence their rate of diffusion is much slower. However, the possibility of flow and diffusion of colloids through capillary openings must not be summarily dismissed, in view of the importance attached to colloidal processes of replacement by some authors.[14]

Frondel, in emphasizing the importance of colloidal processes in replacement, cites the well known evidence that crystallization from an ionic or molecular solution is characterized by an intermediate state of aggregation, that may be colloidal. If this were true of all crystals, it would seriously restrict the mechanisms that might act in replacment. It should be pointed out, however, that the size of the "mosaic blocks" within the crystals, that supposedly correspond to the transitional colloidal particles in the liquid, varies through several orders of magnitude.[15] Furthermore, the evidence for a colloidal transition phase refers to crystalization from a free solution; there is nothing in it to prejudice the formation of crystals by other processes, such as piecemeal diffusion of ions into their lattice positions.

The distinction should be emphasized between three different kinds of "colloidal replacements" which involve: (*a*) filling in or pushing aside of a *previous gel structure,* by a precipitate formed by diffusion of ions through the gel, (*b*) replacement, in which chemical reaction of the replacing ions results in the *formation of a gel,* and (*c*) replacement involving the *transport of a disperse phase* to the replacement front. The latter is the one under consideration here.

Boydell admits that for effective diffusion or flow in replacement, high dispersion must obtain.[16] Even Frondel recognizes the dilemma; in finding

[10] Davtyan, O. K.: Diffusion processes in real solutions of electrolytes, Acad. Sci. U. R. S. S. Bull., Cl. Sci. Tech., pp. 515–545 (1945) [Chem. Abs. 41: 331 (1946)]. Gay, op. cit., p. 82, gives an example of diffusion rate through the capillary pores of gelatin.

[11] Gay: op. cit., pp. 65–70.

[12] Watanabe: op. cit., pp. 112–121.

[13] Watanabe: op. cit., pp. 112–114. Gay: op. cit., pp. 74–77.

[14] Frondel, Clifford: Catalogue of mineral pseudomorphs in the American Museum of Natural History, Am. Mus. Nat. Hist. Bull. 67: 389–426 (1935). Lindgren, Waldemar: Metasomatism, Geol. Soc. Am. Bull. 36: 247–262 (1925). Garrels, R. M.: Solubility of metal sulphides in dilute vein forming solutions, ECON. GEOL. 39: 482 (1944).

[15] Ewald, P. P., and Renninger, M.: The mosaic structure of rock salt, Int. Conf. Physics 2: 57–61 (1935).

[16] Boydell: op. cit., p. 97.

"difficulty in the mechanism of getting a fresh supply of colloid to the solution surface through the layer of already deposited colloid." [17]

A number of the authors cited have pointed out the fact that diffusion through a fluid phase is a particularly convenient mechanism of transport in replacement, because it easily allows the movement of matter to the replacement front and away from it, within the same volume of fluid, each ion moving down its own concentration gradient. Furthermore, the precipitation of an ion at the replacement front automatically provides the impetus for further supply, because removal decreases the concentration of that ion. Another convenient property of diffusion is the decrease of diffusion rate with increasing (ionic) radius, which might separate complex solutions (particularly where it takes place in capillary openings),[18] to give the zoning observed in many replacement deposits.

Reaction.—The processes of exchange acting in and around capillary openings could again be solution and precipitation, peptization and adsorption, or the various combinations of these postulated by Frondel.[19] Of the many factors which will affect solution and deposition in capillaries, some have been treated by Bain, who places particular emphasis upon a combination of Bernouilli's principle and the law of Le Chatelier, by which a decrease of porosity leads to an increase in velocity and a decrease in pressure, leading to *precipitation*.[20] In another part of Bain's paper, the phenomenon of adsorption of ions to the interface is used to explain an increase of *solution* from the walls of the smaller capillaries.[21] Other factors, such as surface tension, dependence of equilibrium on transport, and pressure-volume relations, are discussed by Boydell.[22]

In regard to the *extent* of exchange of matter, the same considerations would apply in the upper part of the capillary size range, as were considered in the case of super-capillary openings. Even on these purely geometrical considerations, however, replacement might reach appreciable proportions in the lower part of the size range. With many capillary openings of the smallest microscopic size, it is conceivable that replacement of a single layer of the walls would represent a significant proportion of the total volume. This would only be the case, however, for extremely porous products. For more compact replacement products, or for more complete replacement, smaller openings are necessary.

"Grain Boundary" Openings.

The possibility of transport of mineral matter through "subcapillary" openings has been mentioned by several authors [23] and considered in detail

[17] Frondel: op. cit., p. 401.

[18] Alexander, J.: Selective adsorption and differential rates of diffusion, Am. Chem. Soc. Jour. 39: 84–99 (1917). Korzhinsky, D. S.: loc. cit.

[19] Frondel: op. cit., pp. 397–401.

[20] Bain, G. W.: Mechanics of metasomatism, Econ. Geol. 31: 515 (1936).

[21] Bain, G. W.: op. cit., pp. 522–523.

[22] Boydell, H. C.: op. cit., pp. 92–97.

[23] Buerger, M. J.: The significance of "block structure" in crystals, Am. Min. 17: 190 (1932). Eskola, P.: A note on diffusion and reactions in solids, Comm. Geol. Finlande Bull. No.

by Perrin and Roubault.[24] Fluids do not move through these extremely small openings according to Poisseuille's equation (with streamline flow); rather, movement takes place by *diffusion* of ions or molecules along the "grain boundaries," probably without regard to the normal state of such particles. For example, if water molecules filled an opening that was but a few molecules wide, almost all would be adsorbed to the walls, and would no longer exhibit the characteristics of the liquid state, though they might still move through the openings by diffusion. I have designated openings of this size as "grain boundaries" for want of a better term; actually they may be present within a single crystal as well as at the boundary between two crystals. As a matter of fact, most real crystals possess *mosaic structure*, a mosaic of blocks or lineages bounded by submicroscopic cracks that originated thermally, mechanically, or by primary growth.[25] These openings, insofar as they may be called openings, are so narrow that the force fields of the walls overlap.

Recent theoretical and experimental work on diffusion under these conditions has been summarized by Barrer, who treats it as a type of *structure-sensitive diffusion*.[26] By this Barrer means that the "disorder" in the lattice (mosaic structure, in this case) is not at equilibrium with a state of "order," and the change from order to disorder, that may have taken place, is not reversible; this distinction is important in lattice diffusion. Matter diffusing along "grain boundaries" does so in accordance with Fick's equation, in proportion to the concentration gradient and the diffusion coefficient. This diffusion coefficient has a different value, of course, than those coefficients governing diffusion of the same material under other conditions. It is smaller than the coefficient for "volume diffusion" through a liquid phase (as discussed above), but larger than that for diffusion through a crystal lattice (as discussed below). Its value depends on the state of aggregation of the host, and to some extent on the temperature and concentration, as well as on the nature of the diffusing matter (specifically, its particle size). As the molecular forces of the walls overlap in these very small openings, they present an energy barrier to movement through the openings; therefore diffusion along "grain boundaries" must be "activated" by the addition of thermal or other energy.

Determinations of the diffusion coefficients and activation energies of all types of structure-sensitive diffusion present difficult experimental problems; inherently, the process is affected by the thermal and mechanical history of the specimen.

Exchange of material that has been transported in "grain boundary" openings will perforce be on a molecular or atomic scale, and will be discussed below.

104, pp. 145–155 (1934). Liesegang, R. E.: op. cit., p. 14. Schouten, E. S.: Structures and textures of experimental replacement in open spaces, ECON. GEOL. 29: 620–621 (1934). Van Hise: op. cit., pp. 143–146.

[24] Perrin, R., and Roubault, M.: Les réactions à l'état solide et la géologie, Bull. du Service de la Carte Geol. Algérie, ser. 5, No. 1 (1937).

[25] Smekal, A.: Kristalleigenschaften und Kristallisationsbedingungen, Z. Phys. 55: 289–303 (1929). Smekal, A.: Structurempfindliche Eigenschaften der Kristalle, Hand. der Physik (2) 24^2: 823–853 (1933). Buerger, M. J.: op. cit., pp. 177–191.

[26] Barrer, R. M.: Diffusion in and through solids, Macmillan, New York, pp. 311–336 (1941). Smekal, A.: loc. cit.

Intra-Lattice Openings.

The movement of matter through crystal lattices has been recognized for some time by metallurgists and physical chemists as a finite and important process. As a geologic process, however, it has not been considered seriously except by Perrin and Roubault,[27] although it was mentioned by Liesegang and Boydell.

Diffusion through crystal lattices has been ably summarized by Barrer.[28] The "faults" or "disorders," which allow the diffusion, may be of the non-equilibrium type (as described above). On the other hand, the disorder may be in equilibrium with the ordered state, and the corresponding diffusion is distinct in some of its characteristics. This type of lattice disorder involves the presence of ions or atoms interstitial to the normal lattice positions, vacancy of normal lattice sites, or both; and it may exist with respect to the positive or negative ions of an ionic lattice, or both. These considerations suggest a variety of situations in an ionic lattice—a number of vacant cation sites balanced by an equal number of interstitial cations, vacant cation sites balanced by an equal number of vacant anion sites, etc. This last type of disorder has been called the Schottky type;[29] and the other types, characterized by interstitial ions, have been named for Frenkel.[30] Diffusion proceeds in accordance with Fick's equation, in proportion to the concentration gradient and the diffusion coefficient. The mechanism of diffusion may involve either the movement of ions or atoms from one interstitial position to another (Frenkel); or a "migration of holes," wherein an atom or ion will move into a vacant lattice site, leaving a vacancy at its former site (Schottky). The conditions which control the type of disorder and diffusion that will obtain in any particular case are not fully understood, but it is obvious that the existence of interstitial ions of a size comparable with the interstitial spaces is not possible without large distortions of the lattice; diffusion of such large ions must be of the Schottky type.

The value of the diffusion coefficient in equilibrium lattice diffusion is very sensitive to temperature change, and in fact may be extremely small at temperatures more that one or two hundred degrees below the melting point of the lattice. At these low temperatures, the disorder becomes "frozen," and is then structure-sensitive in that its nature depends on the history of the specimen. The diffusion coefficient may be calculated approximately from known energy values, lattice constants of the host, and the radius of the guest. The energy of activation for equilibrium lattice diffusion is in general greater than that required to activate structure-sensitive diffusion.

[27] Perrin, R., and Roubault, M.: op. cit., p. 56. A close distinction is not made between grain boundary and intra-lattice diffusion in most of this paper.

[28] Barrer, R. M.: op. cit., pp. 239–310.

[29] Schottky, W.: Über den Mechanismus der Ionenbewegung in festen Electrolyten, Z. Phys. Chem. 29B: 335–355 (1935).

[30] Frenkel, J.: Über die Warmebewegung in festen und flussigen Körpern, Z. Phys. 35: 652–669 (1926).

SOLID PHASE REACTIONS.

The exchange of matter, that has been transported by means of diffusion through "openings" of sub-capillary size, is almost inextricably involved in the subject of reactions between solid phases; and conversely, true solid phase reactions are difficult to conceive as taking place without diffusion of this type. After equilibrium has been reached, ions or atoms which have so diffused into a crystal may exist either at lattice points of the original crystal (previously vacated), or at interstitial points. If the distribution of the diffused matter is regular, the product is a compound; if the distribution is random, it is a solid solution. Considered broadly, however, both processes represent reactions.

A wide range of work on reactions in the solid phase has been summarized by Hedvall,[31] and to a lesser extent by Jost, Taylor, and Wagner.[32] Applications to geologic problems have been considered in some detail by Perrin and Roubault, but have received little attention elsewhere.[33]

Factors.—In general, factors that will affect the rate and equilibrium point of the reaction are: the temperature (its relation to transition temperatures and to melting points), the area of interface at which the reaction is taking place (including germination), and the rate of supply. If a gas is formed in the reaction, the law of mass action will be partially effective in determining the rate and equilibrium point.[34]

Relation to Diffusion.—The relation between diffusion and reaction in the solid phase, is three-fold. In the first place, the chemical process may supply the energy necessary to activate the diffusion, or "loosen the lattice"; if the net result of the whole reaction process represents a decrease in free energy, the reaction will be spontaneous. The rate at which the chemical process takes place will govern the rate of diffusion insofar as it affects the concentration gradient; and conversely, diffusion may limit the supply available at the interface. In some cases, therefore, the overall rate of reaction is limited by the rate of diffusion, and in others it is not. Finally, the nature of the product formed by the combination will affect the rate of diffusion, because the diffusion must take place (at least in part) through this product.

This last point should be emphasized, because it bears directly on the geological problem. Although there is some evidence of centrifugal formation of pseudomorphs, the reaction interface will usually be moving away from the source of supply. This means that the type of opening available for transport to the interface is determined by the state of aggregation of the *replacement*

[31] Hedvall, I. A.: Reaktionsfahigkeit fester Stöffe, Barth, Leipzig, 1938, 224 pp.

[32] Jost, Wilhelm: Diffusion und chemische Reaktion in festen Stöffen, Steinkopf, Dresden, 1937, pp. 180–221. Taylor, N. W.: Reactions between solids in the absence of a liquid phase, Am. Cer. Soc. Jour. 17: 155–161 (1934). Wagner, C.: The mechanism of the movements of ions and electrons in solids and the interpenetration of reactions between solids, Far. Soc. Proc. 34: 851–859 (1938).

[33] Perrin, R., and Roubault, M.: op. cit. Eskola, P.: op. cit. Taylor, N. W., and Williams, F. J.: Reactions in the solid phase in the system CaO-MgO-SiO_2 in the temperature range 600–1200° C., Geol. Soc. Am. Bull. 46: 1121–1136 (1935).

[34] Zawadski, J., and Bretsznajder, S.: Some remarks on the mechanism of reactions of the type: solid = solid + gas, Far. Soc. Proc. 34: 951–959 (1938).

product. This principle applies to all types of openings, and has been noted by several geologists.[35]

Volume-for-Volume Replacement.—The question of "volume-for-volume" replacement is related, at least in some cases, to the same factor called upon previously: state of aggregation of the replacement product. A non-compact, permeable state is conducive to easy transport and faster and more complete replacement, but it may also allow a stoichiometric reaction to be 'volume-for-volume." Therefore, the criterion for the lack of stoichiometric reaction in replacement should not be volume relations, but mass relations of the reagents and the products. If there has been no volume change since reaction, the specific gravity of the product may be compared with that postulated for the host. It must be remembered also, that the stoichiometric product may be subsequently or simultaneously diluted by the adsorption and diffusion into it of excess matter, with which it forms a solid solution or an "interstitial compound." [36]

The above outline presents only the broader aspects of the processes of replacement. It has not been intended to give the details of theoretical calculations, experimental methods, and results obtained. However, it should not be inferred from the lack of experimental documentation that these processes are not substantial; on the contrary, processes such as solid state reactions, for example, are known to proceed in a pure form, with finite velocity, in many systems. Many details and extensive bibliographies will be found in the general summaries referred to.

A RECENT EXAMPLE.

Consideration of a recent article by Douglas, Goodman, and Milligan,[37] will illustrate the use of the above analysis. The authors describe three of a number of possible processes active in metasomatism. These will be discussed in turn and related, in so far as they can be, to the possibilities that have been outlined above.

Pseudomorphs.—The single sentence devoted to this subject does not make clear exactly what the process consists of. The author states that it "implies the removal of an already formed mineral, and the filling of the resulting open space by the 'replacing' mineral. . .," but there is no statement as to the scale on which the removal and filling proceed. If the statement means (and I so interpret it) that an entire crystal or group of crystals is removed before any filling takes place, then it may or may not be cavity filling, depending on one's definitions. In that case, the result would represent only one type of what are usually recognized as pseudomorphs. If the

[35] Boydell, H. C.: op. cit., p. 83. Irving, J. D.: Replacement ore bodies, ECON. GEOL. 6: 558 (1911). Liesegang, R. E.: Colloid chemistry and geology: in Alexander, J., Colloid Chemistry, Chem. Cat. Co., New York, pp. 251–260, 1931. ("The formation of pseudomorphs is no proof of the possibility of diffusion in crystals. . . .") Locke, A.: The opening as a reason for ore, ECON. GEOL. 23: 93–98 (1928).

[36] The variability of mineral compositions by solid solutions is well known. In addition, some crystals do not even follow the "law of equal proportions"; the lattice reactions leading to such variations are discussed by Barrer: op. cit., pp. 249–250.

[37] Douglas, G. V., Goodman, N. R., and Milligan, G. C.: On the nature of replacement, ECON. GEOL. 41: 546–553 (1946).

statement means that the replacement takes place on any smaller scale, then almost any of the many processes considered above might have been active. Even if some of the processes postulated by Frondel [38] are discounted, the variety of textures and compositions exhibited by forms called pseudomorphic, indicates a variety of processes of formation. The use of the term "pseudomorphs" or even pseudomorphism, as a specific process, therefore seems inappropriate.

Hydrodynamics.—The precise nature of this "process" is likewise in doubt. In a previous publication [39] the hydrodynamical *factor* was described in relation to ore deposition. After first stating that *space filling* only would be considered, the author describes the effects of turbulent flow in ore deposition. At a later point in that article,[40] and similarly in the article first mentioned, the author considers the *replacement* of a slate to be hydrodynamic. As described, it involves "softening" of the rock material, removal in solution or by flushing, and subsequent deposition of the "replacing" mineral in the open space produced. The nature of the softening is unknown (though it may be very important in the process as a whole) and the entire concept seems to be a not very well defined group of processes, rather than a definite or single one. The hydrodynamical nature of these processes, except perhaps the "flushing," is not clear. In the capillary or smaller openings in which the greatest part of replacement must ultimately take place, turbulence is virtually impossible.[41]

Atom Shunting.—This concept, while more definite, presents some anomalies. The authors quote Bateman's succinct statement of the problem, "The *copper* must penetrate a dense layer of *chalcocite* in order to arrive at the interior front of replacement, and the dissolved iron from the pyrite must escape through the same layer of compact chalcocite" [42] (italics mine). In the model which they describe, however, a *copper ion* is required to move through a *pyrite lattice*. Actually, as soon as a layer of copper sulphide has been formed, it will be this layer of copper sulphide that the copper must move through, or displace by "shunting." As soon as the limit of solubility of copper in the pyrite lattice is reached, the lattice will transform to that of chalcocite or some other sulphite, probably with mechanical disintegration into a fine aggregate.[43] The experiments support this conclusion, if the chalcocite obtained was very finely crystalline, as seems to be indicated.

If the chalcocite were crystalline and finely divided, replacement would take place by diffusion through the grain-boundary or possible capillary openings between the grains of chalcocite, with exchange reaction at the interface.

Even if this were not the case, and it were necessary for a copper ion or

[38] Frondel, Clifford: loc. cit.

[39] Douglas, G. V.: The hydrodynamical factor in ore deposition, Am. Jour. Sci. 243A: 122–124 (1945).

[40] Douglas: op. cit., p. 131.

[41] Tolman, C. F.: Ground Water, McGraw-Hill, New York, p. 200, 1937.

[42] Bateman: op. cit., p. 95.

[43] In some cases of replacement, the crystal framework may remain intact beyond the limit of solubility, as an open network in a strained, metastable state. In the case in question, the mutual solubilities are apparently negligible; see Palache, Charles, Berman, Henry, and Frondel, Clifford: A System of Mineralogy, Wiley, New York, vol. 1, pp. 188 and 284 (1944).

an iron ion to move through a pyrite lattice, it may be seen by reference to the discussion of processes in the present paper, that the mechanism proposed is identical to a Schottky-type diffusion in which there is a "migration of holes" through the lattice. Whether or not an iron atom is pushed out by a copper atom, or the iron atom moves out and leaves a hole behind to be filled by a copper ion, is immaterial.

The apology by the authors for the use of electrical energy to accomplish the diffusion is well founded. As a matter of fact, solid state diffusion and reaction may be treated theoretically as a simple cell.[44] It should be remembered, however, that pyrite exhibits a combination of electronic and ionic conductivities. This may explain the lack of reaction in Experiment No. 3, the conduction being principally electronic, as there was no mechanism for the removal of ions.

In regard to the experiments, it should be pointed out that the iron found in solution in Experiment No. 4, may have been a normal result of electrolytic attack of hydrochloric acid on pyrite; this could be checked by running the experiment with a metallic connection below and the HCl solution above, the opposite of Experiment No. 3. Furthermore, for Experiment No. 4 to be wholly satisfactory, the solution should have been checked for sulphide ion.

CONCLUSIONS.

The processes of transport and reaction operative in metasomatism may be provisionally classified according to the size of openings in which they are operative. In openings of capillary size, diffusion of ions through a fluid phase may be more effective in transporting normally solid matter, than mechanical transportation by the fluid. In "grain boundary" and intra-lattice openings, transportation must take place by diffusion through the solid phase, and reaction may take place without the presence of a fluid phase. Although the larger openings are important for fast transportation of large quantities of material to the vicinity of the replacement front, complete, fine grained replacement may be accomplished only by transportation and reaction in much smaller openings. These openings may be made available by a loose state of aggregation of the replacement product.

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[44] Hoar, T. P., and Price, L. E.: The electrochemical interpretation of Wagner's theory of tarnishing reactions, Far. Soc. Trans. 34: 867–872 (1938).

THE UBIQUITY OF GOLD VALUES AND THEIR RELATION TO ZONES OF TENSIONAL DILATION.

W. JAMES BICHAN.

ABSTRACT.

The importance of a study of the distribution of gold and metal values in lodes and massive deposits.

The contrast between conditions at surface and those at depths where hypothermal and magmatic deposits may be presumed to have had their inception. The improbability of water having been the medium of metal transport at great depths.

An examination of the implications of the probably erroneous assumption that gold has remained at the original points of separation or precipitation from the mineralizing fluids.

Outline of the proposition that gold, having been one of the last minerals to crystallize, has frequently undergone extensive migration during the final stages of mineralization.

The mobile fluidity of gold during the later stages of vein formation; its migration from zones of compression to zones of tensional dilation. Parallelism of the features of gold distribution with the ubiquitous nature of quartz-veining. The confinement of minerals to zones of tensional dilation dependent upon the orientation of stresses immediately prior to crystallization.

Summary of the evidence visible to the eye in support of the foregoing conception. The logical basis upon which the known phenomena of gold distribution and habits may be adequately explained and forecast.

The products and processes of mineralization through crystallization from a melt contrasted with those to be expected through precipitation from an aqueous solution.

Concept of mobile late-stage fluidity extended to minerals other than gold.

THE distribution of gold values is a matter of general importance, as well as one of extreme bafflement. There are few natural phenomena to which so many conflicting "rules" have been applied. At the present time, when it seems at last probable that some research having a direct bearing upon this factor will be done, a timely word of warning may be in order. Lest all our investigations be diverted along one channel, running the risk of potentially unproductive labors, it is believed that we should adopt a more sceptical and questioning attitude towards the hydrothermal theory of origin for mineral deposits. This is the theory currently popular, a hypothetical means of explaining the intricate processes by which all manner of minerals, from those formed at shallow depths and normal atmospheric pressure, to those formed at great depths, under high pressure and elevated temperature, have found their place. The arguments upon which such a theory is based are by no means so clear-cut, nor so directly applicable, as is generally supposed. Especially is this the case when the deep-seated ores come under consideration.

This class includes those occurring in compact, thoroughly recrystallized rocks, and in close association with great igenous rock masses.

The following presentation is intended to focus attention upon a probability previously given scant consideration, but one that serves to endow with logical meaning the inferences to be drawn from the ubiquitous nature of gold occurrence. Perhaps it can also be extended to provide an immediate basis for a quantitative theoretical and experimental approach to the assessment of the extent and relative worth of gold concentrations.

The analogy between hypothermal metal-bearing deposits and emanations giving rise to hot-springs and fumaroles appears remote when considering the actualities of bodies of mineral wherein quartz and the silicates are a common association. The affinity with magmas and igneous rocks in general is too close. Conditions within the confining environment were vastly different from those at the earth's surface, and there should, therefore, be little else but contrast between the resultant products. Even surface conditions at the time of formation of many hypothermal and magmatic deposits must have shown a decided variation from those existent today. This difference would be particularly well marked in comparison with the pre-Cambrian periods of ore-formation.

Beyond the fact that fluid solutions appear to have been associated with both fumaroles and deep-seated mineral deposition, it is no more reasonable to state unconditionally that a deposit is of hyprothermal origin than it would be to maintain that all crystalline aggregates in the vicinity of fumaroles had been deposited from liquid solutions. Some of the latter have been precipitated from gaseous solutions or sublimations, and it is equally probable that the solvent mineral-bearing fluid agent in the depth of the crust was not exclusively water. In fact it can be shown that there are many and cogent reasons why it is highly improbable that water was the universal medium of material transport, whether in the liquid or gaseous state.

At the outset we should examine the widely assumed concept that the precious metal content of a primary lode always appears in the place of its original deposition. This generalization of course excludes the travel of gold particles through the oxidized zone of certain bodies to the vicinity of the water table. The latter has been termed a secondary process.

A world-wide study of gold occurrences of relatively deep-seated origin, both in the preliminary development headings and working stopes and in thin sections under the microscope, leads to the conclusion that gold has rarely remained at the original point of separation or precipitation from the mineralizing fluids. Such cases are believed to be exceptional and dependent upon the commencement of crystallization of the gold prior to the consolidation of much of the quartz gangue.

It is generally conceded that the usual habit of gold is to crystallize *late* in the vein sequence. The additional implications of the late crystallization of gold are deserving of further close study. It should not be assumed that the introduction of the gold into the general environment of its occurrence has been one of the most recent geologic events, implicit in the observable fact of its relative lateness of crystallization.

It does not follow that the gold-depositing fluids have entered the scene at a stage in the geologic history remote from that in which quartz or other major phases of mineralization appeared. We do not assume that the interior of a loaf has been set within the crust *after* the crust has been baked and hardened, simply because we are aware that the inside has lost its doughy consistency late in the sequence of events.

All that can with certainty be inferred from the megascopic and microscopic observations to the effect that gold has crystallized late is at present limited to this statement: it has *crystallized* late. Many observations show that gold is generally the last mineral to crystallize in a typical quartz environment, although galena, sphalerite, chalcopyrite, and pyrrhotite are closely associated in time in so many instances that the exact relationships in the final stages often remain obscure. The five minerals have been known to exhibit mutual boundaries, from which phenomenon it is impossible at present to draw definite conclusions regarding the paragentic sequence.

This statement can be made on the basis of empirical justification: gold commonly crystallizes later than quartz or other silicate minerals, and later than pyrite, magnetite, ilmenite, specularite and arsenopyrite of its own generation.

Together with the observation of the place of gold in the general paragenetic sequence of the metallic minerals, it can be recorded, in view of evidence painstakingly collected by Mr. Frank Ebbutt, that there is hardly a single common mineral species nor rock type within which native free gold does not occur, or has not at some time been reported.

The common association of gold with intensely fractured quartz, whether recemented or not with minerals of a later generation, is also well known.

If in the extant literature on the subject, it may be permitted to substitute the word *penetrated* for such expressions as "deposited," "precipitated," or "replaced," then the general nature of the thesis to follow will become apparent.

At the temperature and under the conditions of crystallization of the quartz in deep-seated veins, it is submitted that metallic gold would possess the mobility of mercury at atmospheric temperature. This would become especially marked in cases where the melting point and the viscosity of the gold were lowered significantly through the presence of small amounts of impurities, metallic or otherwise.

The mobility of gold during the late stages of quartz crystallization in veins and veinlet aggregates is considered to be a possible logical reason for the extreme variability of the tenor of such deposits. This feature has not been satisfactorily accounted nor explained in any other way. Neither has any explanation in this fashion been previously put forth.

Fracturing due to stresses affecting the environment in the later stages of consolidation can be inferred from direct observation. The shattered and brecciated nature of some sections of the veins, and the penetration of these zones by late fluid fractions depositing calcite and other minerals in minor amounts, confirm the indications that such cracking took place before the mineralization processes had been completed.

It is submitted that the migration of gold in a state of fluid mobility has almost invariably occurred during the late period of fracturing undergone by the quartz, and other hard brittle minerals, in the vicinity of this class of gold deposits.

The direction of travel of the gold would necessarily be from zones of compression to those neighboring sections where tensional dilation was possible, *i.e.* zones of incipient tension. In many instances the gold may not have travelled far by comparison with the width of a deposit, perhaps through distances to be measured in inches. In yet other instances it is conceivable that repeated shocks and changes in the orientation of externally applied stresses would allow the gold to migrate through distances that might be estimated in hundreds of feet.

The evidence visible to the eye, whether in the hand specimen or the microscope slide, points to this conclusion: that the normal mode of occurrence of gold along fractures, along thin thread-like slip planes, as ramifying veinlets, and as smears along slickensided surfaces, is explainable most logically only if it has penetrated these crevices in a fluid condition during times of local and temporary relief of stress. A repetition of the pressure, *after the gold had crystallized,* has been responsible for the frequent appearance of smeared and flattened films and flakes of gold along plane surfaces in many types of deposit.

The distinctive concentration of gold values into shoots, separated by zones of relatively barren vein material, is the logical outcome of the lateral or vertical migration of gold in a state of mobile fluidity, from those zones of extreme pressure, or compression sections, to the nearest convenient tension zones. The latter existed in a state of potential tensional dilation on a scale favorable to the reception of the more mobile constituents of the veins at that time.

It may further be inferred that the extreme localization of important zones of quartz veining may have been controlled through similar and parallel migration of the quartz-depositing fluid during antecedent stages in the mineralization process.

Gold values are thus believed to have become localized along zones of tensional dilation within the sphere of original introduction of the gold-bearing fluids. Similarly, it may be considered that quartz veining of potential economic worth is confined to zones of tensional dilation distributed at intervals along the strike of the access channelways through which the vein-forming solutions arose.

The distribution of these highly important zones of tensional dilation was apparently dependent upon stress conditions under which the crustal environment existed immediately prior to the introduction of the mineralizing fluids. Stress conditions immediately following the crystallization of the bulk of the quartz have in turn determined the final localization of the gold values.

It has also been observed in certain localities that intervening fluid fractions, from which a portion of the vein material was deposited, were also affected by periodic reorientations of directive stresses at the time of their proportionate fluidity. After a certain barren period of quartz consolidation

it may be observed that there has been a redistribution of the later siliceous fractions, from which a certain portion of both the quartz and the metallics have subsequently crystallized.

Late redistribution may be accompanied by the insulation and sealing-off of the early barren quartz from the channels through which the solutions carrying the gold are moving, thus assisting in the isolation of the values.

Frequently, minerals other than gold appear to have been affected by the late redistribution of fluid fractions.

It is contended that the mobile fluidity of gold within the near vicinity of a quartziferous influx is physico-chemically possible under the conditions of temperature and pressure to be contemplated. It is suggested that this will prove a fruitful concept in any attempt at the unravelment of causes of grade distribution in gold deposits throughout the pre-Cambrian.

Although this picture of events cannot be conclusively proven until a great deal more research is undertaken and satisfactorily completed in the field of the high pressure chemistry of solutions and melts of diverse types, nevertheless it is offered in the hope that those instituting and carrying out such work will retain an open mind on the whole question of underlying causes. It may be wise to entertain as alternative theories all modes that are suggested by observation, and that are neither physically nor chemically impossible of attainment under conditions of elevated temperature and extreme pressure, comparable with those believed to have existed under hypothermal conditions.

In conclusion, the following summary is presented to provide a contrast between the observable characters of a metal that has crystallized from its melt and the deposit of a similar metal that might be presumed to have been precipitated from a hydrothermal (aqueous) solution:

(1) Melting point depressants would probably be important in the case of a melt. It is known that lead depresses the melting point of gold to the extent of several hundred degrees, and almost in direct proportion to the percentage of lead present, for amounts of lead not exceeding the quantity of gold. Other metals and minerals are known to have a similar effect. The determination of a solvent for gold, and for many other natural minerals usually considered "hydrothermal" has never been adequately concluded, neither by deduction nor by experiment.

(2) With crystallization from a melt there is no outlet required for the superfluous fluids, as with the case of deposition from circulating solutions. If gold were deposited from fluids of later origin than those that deposited quartz, both an inlet and an outlet would show evidence of their previous existence. Gold specimens characteristically show their films of gold thinning out along a crack that gradually becomes imperceptible in the body of the mass, and does not suggest the exodus channel of any solution from which it might have been deposited. This phenomenon is shown on a larger scale by quartz veinlets and lenticles. These suggest nothing so clearly as the possibility that the quartz has almost completely filled the fissures and zones of dissolution along the borders of the latter. Further movement of fluids has

been effectively blocked by a recurrence of the lateral pressures imposed by the resistance of the wall-rocks. This feature is given particular emphasis by the lenticular character of most quartz occurrences, and the fact that these, in common with the gold on its smaller scale, appear to feather out to minute cracks that eventually disappear altogether in all directions.

(3) The temperature range of deposition from a melt varies with the impurities present. Crystallization is dependent upon the downward shifting of those isothermal horizons within the earth's crust at which the gold-bearing fluid can become stabilized. Before deposition can commence from a hydrothermal solution, it first must reach a sub-crustal horizon at which it is saturated with respect to gold. Crystallization, or settling out from solution, would then continue until the gold content had been eliminated (or the solution poured out upon the earth's surface?). The net effect of this contrast in conditions is that crystallization from a melt could take place throughout the crustal range of thickness, at the time of entry of the gold-bearing fluids, provided that the crustal temperatures were above a certain stated minimum of a few hundred degrees (depending upon the constitution of the fluids). These fluids need never have been saturated with respect to gold. Certain related fluids are known to have contained negligible quantities of the metal. Hydrothermal gold-depositing solutions would not only have to show a very significant variation of the saturation amount for minor variations in temperature, in order to bring about deposition on any scale, but the amount of deposition could only be strictly limited since: (i) the gold content can only be considered to have been low, judging from experimental data available; and (ii) the ratio of the amount deposited to the total content in the solution will also have been small. Thus, due to the gentle slope of the temperature gradient within the crust, we should have to postulate the movement of enormous quantities of solution. The vagaries that must have been shown in the choice of movement channels by solutions of this nature involves great detail and little in the way of concrete satisfaction.

(4) The contrast between the minute quantities of fluid required to be present in the ultimate crystallization from a melt and those prerequisite to hydrothermal deposition is a fundamental one. The enormous quantities of solution of the character of the latter are further emphasized by the fact that the solutions would have to maintain their movement; otherwise the solvent should crystallize with the gold or remain in its vicinity in some form. The dryness of most deep gold mines is too well-known to need further substantiation. Therefore the hydrothermal solvent was apparently non-existent, or has had time to vaporize.

(5) Crystallization from a melt is an internal process once the gold-bearing quartz is in place. The reasons for the particular selection of a quartz-environment by the *externally* derived hydrothermal solutions that might have brought in gold at a late stage are not apparent.

(6) The homogeneous equigranular crystal structure of the larger masses of native gold suggests crystallization from a melt by analogy with metallographic textures. It is strongly in contrast with the banded character of

hot spring deposition, the only type known of certainty and from direct observation to have been derived from hydrothermal processes.

(7) The compact texture of native gold is in distinct contrast with that of metals that have been obtained from solution, *e.g.* through processes of electrolytic deposition. These are notably porous and frequently have to be worked before they can become useful from the standpoint of their metallic qualities.

(8) In melt-derived aggregates, the proportion of gold to silver, or of gold to other minerals, would depend on the proportions present at the time of original (primary) separation from the gold- and quartz-bearing fluids. Crystallization from solution should produce only a very slight variation in gold-silver ratios throughout any given deposit. The wide divergence possible in individual samples sent for assay here again startles one's credulity in the competency of the supposed hydrothermal process.

(9) Since the late solution fractions would have to pass any one locality throughout a great period of time, from previous reasoning it is hard to conceive that they would not deposit various other minerals during some proportion of this time. These would be "late" and of contemporaneous deposition with the gold. Gold as the sole solute would appear to be an extreme and unusual case of a high degree of selection and indicate a very special solution composition. Gold smears along planes of movement show no evidence of any important quantity of accompanying mineral. An improbable uniformity of homogeneous hydrothermal solution would have to continue passing any given point in order to deposit nothing but gold.

(10) A difficulty in the hydrothermal process arises when an attempt is made to account for the gold particles locked up in pyrite or arsenopyrite, which minerals appear to have belonged to earlier stages of deposition. This objection disappears when it is conceded that the gold may have become isolated within the growing sulphide crystals while, still in the molten state.

In a recent article on the geology of Falconbridge, Stan Davidson has this to say:

> The term hydrothermal for the later stages which deposited the sulphide mineralization is perhaps a misnomer. It would seem that the conception of an ordinary dilute hydrothermal solution is inadequate when the very large amounts of sulphide deposited are considered.[1]

One might go further than this and suggest that in the formation of massive sulphides, as with gold, hydrothermal is in many instances not only a misnomer, but a prime misconception. It cannot stand the test of practical possibility. A great many of the difficulties attendant upon currently popular theories of sulphide genesis would disappear if deductions were limited to what is implicit in the observation that certain of the sulphides have crystallized later than others and later than the adjacent minerals of igneous derivation. Their introducton could equally have been contemporaneous or earlier. So far as current evidence and reasoning can prove, the paragenetic

[1] S. Davidson: Structure at Falconbridge Mine, Bull. C. I. M. 49: 503, 1946.

sequence indicates little regarding relative age of introduction. This opens the way to the further implications of the possibility of sulphides having been separated or introduced in the fluid state, and remained in that condition throughout entire geologic epochs and periods, provided that the crust were to rest in a relatively stable condition and that there were little shifting of the geotherms. But that question will have to stand for another time.

UNIVERSITY OF NEW BRUNSWICK,
FREDERICTON, N. B., CANADA,
April 8, 1947.

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MANHATTAN

REVIEWS

Le Congo Physique, 3rd Edit. MAURICE ROBERT. Pp. 452; figs. 70; pls. 29. H. Vaillant-Carmanne, Liège, Belgium. Price: 400 francs.

This is the 3rd edition of "Le Congo Physique," the first of which was published 25 years ago. The author is well known as professor at Brussels University and honorary Chief of the Geographical and Geological Service of Katanga, Belgian Congo. He was one of the pioneers of geological investigations in Central Africa, and organized the Geographical and Geological Service of Katanga and, for many years, conducted the work of this service in the field.

The book is divided into 11 chapters. The first chapter deals with European penetration in the regions of Central Africa and develops the idea that this penetration was subjected to the physical environments of those regions. The Europeans started, not from the Atlantic Coast, but from the East Coast, and succeeded in penetrating into the interior of the Congo Basin.

One hundred pages deal with Congo geology. A large mass of continental sediments has remained almost horizontal and is represented by the Karroo and the Kalahari systems; these beds overlie more ancient formations that constitute the basement of Africa. The overlying beds are fossiliferous and their age can be accurately determined. They range from middle Carboniferous to Pleistocene.

The book deals with these beds in detail. They contain mineral deposits which play a major part in the economy of Central Africa, chiefly of coal and diamonds.

Through the absence of fossils, or at least of chronologically significant fossils, the geology of the older formations has been particularly difficult to trace. Nevertheless, for this geology the author gives outlines which he considers as quite accurate. In plenty of details, he describes the beds of the Kundelungu system, of the schisto-dolomitic system and then the formations of the Kibara system and, lastly, the basement complex.

The Kundelungu system is considered to be Paleozoic, whereas the subjacent systems are of Algonkian age except for the lower part of the basement complex which appears to be Archean.

The younger beds have not been folded, but just warped during the Miocene; nevertheless they were subjected to large scale faulting which appears in the African grabens.

The older beds were subjected to repeated folding in the course of three major orogenic periods. During the older one, the folding of the basement complex, the next, called the Kibarian orogenic period, occurred, displayed itself towards the end of the Kibara; and the last, known as the Kundelungu folding, was paroxysmal towards the end of the Kundelungu period.

The mineralization is considered in the third chapter and is intimately bound to the orogenic periods. The great gold mineralization belongs to the folding of the basement complex. The outsprings of the tin mineralization were brought by the acid magmatic eruptions of the Kibarian folding. As for copper, the mineralized beds, which are so important in Katanga and in North Rhodesia, are associated with the Kundelungu foldings. Uranium belongs to this same orogenic period.

The mines are described in full detail, with estimates of the tonnage of visible and of probable ore. Fifty pages are devoted to mineral and metalliferous beds.

Chapter four deals with orography and hydrography. It is an important chapter of the physical geography of Central Africa. Therein are studied the evolution of the face of the continent, the description of relief and hydrography and also the graben; not only those of Central Africa, but even those of East Africa. Each one of the regions of the Congo Basin is studied in detail, from the point of view of orography as well as hydrography.

The study of climate covers 53 pages. Congo climatology is given after that of Africa as a whole. The following questions are reviewed: equatorial climate; Sudan climate; "aridity index," evaporation, insolation, radiations and light, transparence of the air and bioclimatology. Numerous drawings illustrate this chapter and maps of monthly rainfalls are given. There is a paragraph on paleoclimatology.

The rate of flow of Congo rivers is the object of chapter six. The sites of water power have before them a great future in the Congo. The resources are detailed and an accurate description is given of those resources which have hitherto been industrially exploited.

Underground hydrology is given a dozen pages.

As for soil, it is the object of an important chapter, namely chapter nine, which refers to the alterations in tropical regions and more particularly of the laterite. Superficial soils are studied and classified and their classification gives rise to important annotations. The fertility of tropical soils, which is so important for the agricultural exploitation of the country, is considered in great care. So is the question of the erosion of soils cultivated either by natives or by Europeans.

Chapter ten, devoted to an essay of biogeography, was written by the author with the collaboration of several well informed experts. It is 54 pages long and gives up-to-date data about the flora and fauna of Central Africa.

Consideration suggested by the study of the physical environment terminates the volume.

An abundant and up-to-date list of references, although printed in small types, covers 11 pages, and 13 pages of index makes the book a ready reference.

G. O.-E.

PRINCETON, N. J.,
April 6, 1947.

Fundamentals of Earth Science. By HENRY DEWEY THOMPSON. Pp. 461; figs. 304. D. Appleton-Century Co. New York, 1947. Price, $3.45.

The general purpose of this book is to knit together in one volume the fundamentals of geomorphology, geology, mineralogy, and geography or meteorology, to provide a balanced one-semester survey of earth sciences and to provide a basic text book for beginning geology or geography. The content of the book may be gleaned from its 26 chapter headings: historical development; the earth as a planet; origin and age of the earth; general composition, structure, and processes; maps, diagrams, and photographs; weather and climate; climatic controls and types; weathering; work of streams and stream cycles; ground water; glaciers and glaciation; wind work; lakes and swamps; oceans; minerals; volcanism; igneous, sedimentary, and metamorphic rocks; movements and structure of the lithosphere; earthquakes; land forms; earth history; useful aspects of earth science; brief bibliography, and index. Each chapter closes with "suggestions for further reading." The subject matter is planned to provide for the cultural needs of freshmen and at the same time stimulate interest for those who wish to specialize later in geology or geography. Kirtley Mather points out, in his introduction to

the volume, that it is not just a rehash of the old familiar story but impresses him as being refreshingly new.

The book is outstanding for its clarity of presentation and sustained connection. Its contents are largely the familiar classical material of elementary text books. The illustrations are numerous; many of them are aerial photographs, but most of them are the old-time classical illustrations and photographs familiar to past students of elementary geology. Unfortunately the photographs have been reproduced on unsuitable paper so that the effectiveness of most of them is lost.

Elements of Engineering Geology, 2nd edition revised. H. RIES and T. L. WATSON. Pp. 469; figs. 293. John Wiley & Sons, New York, 1947. Price, $5.00.

The predecessor of this book was Engineering Geology which appeared in 1914. This was condensed, simplified, and revised as Elements of Engineering Geology in 1921 and became the standard text in engineering geology. The second edition appeared in 1930 and this revised second edition follows after a lapse of 17 years.

The general plant of the book is similar to its immediate predecessor but considerable revision is noted. The 14 chapters deal with minerals, rocks, structural features, weathering and soils, rivers, subsurface water, landslides and subsidence, coastal processes, lakes and swamps, glacial deposits, reservoirs and dam sites, road foundations and road materials, ore deposits and historical geology. The most extensive revision appears to be in the parts dealing with dams, reservoirs, and road foundations and road materials. Other matter has been brought up-to-date and examples and reference lists modernized. Many new illustrations appear. In its new form the book should continue to occupy the important place held by its predecessor.

This Great and Wide Sea. By R. E. COKER. Pp. 325; figs. 23; pls. 90. University of North Carolina Press, Chapel Hill, N. C., 1947. Price, $5.00.

This rather unusual book brings together all features of the oceans in the fields of history, exploration, chemistry, physics, geology and biology. Part I, History and Geography, deals in five chapters with the discovery of the seas, beginnings of oceanography, pioneers of oceanography, oceanography in America, and sea and land. Part II, Chemistry and Physics, contains seven chapters dealing with the sea as a solution, its physical properties, bottom deposits, circulation, waves, tides and other movements, and the sea and the sun. Part III, Life in the Sea, also has seven chapters, relating to general conditions, pasturage of the sea, plankton, bottom life, and nekton, or the life at large. Many page-size photos illustrate the sea life.

For one interested in oceanography and particularly sea life the book is packed full of information. It makes pleasant reading for itself and a good index will give it usefulness as a reference book.

BOOKS RECEIVED

ALAN T. BRODERICK.

Nickel-Bearing Laterite, Red, Flat, Curry County, Oregon. F. W. LIBBEY, W. D. LOWRY, R. S. MASON. Pp. 10; fig. 1. Oregon Dept. Geol. and Mineral Inds. "The Ore Bin," vol. 9, No. 3. Portland, 1947. *Preliminary shallow drilling of peridotite laterite (Pliocene) shows .27 to 1.46% Ni associated with limonite. Ni increases with depth.*

Geologic Map of Ohio. J. A. BOWNOCKER, G. W. WHITE AND OTHERS. Ohio Geol. Survey. Columbus, 1947. *30″ × 38″, colored, 1 section, scale 1:500,000, revised 1947.*

The Geologic Interpretation of Scenic Features in Ohio. J. E. CARMAN. Pp. 42; figs. 38. Ohio Geol. Survey Reprint Series No. 3. Columbus, 1946.

Ground Water in the Fargo-Moorhead Area, North Dakota and Minnesoto. A. C. BYERS, L. K. WENZEL, W. M. LAIRD, P. E. DENNIS. Pp. 87; figs. 7; pl. 1. U. S. Geol. Survey. Washington, 1946.

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Monterey Formation of California and Origin of its Siliceous Rocks. M. N. BRAMLETTE. Pp. 55; plgs. 19. U. S. Geol. Survey Prof. Paper 212. Washington, 1946. *Thick Miocene formation of diatomite, porcelanite, cherty shale, chert, bituminous beds. Cement in dense rocks from diatom solution and silica precipitation, partly diagenetically, mostly later by load and deformation. Correlation over wide area.*

Geology of Quadrangles in New Hampshire and Vermont. New Hampshire Planning and Devel. Comm., Concord, 1946. *Geological history of each clearly illustrated by series of block diagrams. Texts are largely in non-technical language.*

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The Geology of the Plymouth Quadrangle, New Hampshire. C. B. MOKE. Pp. 21; figs. 5; pl. 1; map, colored, 12″ × 17″, scale 1:62.500.

The Geology of the Mt. Washington Quadrangle, New Hampshire. M. P. BILLINGS, K. F. BILLINGS, C. A. CHAPMAN, R. W. CHAPMAN, R. P. GOLDTHWAIT. Pp. 56; figs. 32; map, colored, 12″ × ″17, scale, 1:62.500.

Secondary Recovery of Petroleum in Arkansas—A Survey. G. H. FANCHER, D. K. MACKAY. Pp. 264; figs. 132. Arkansas Oil and Gas Comm. El Dorado, 1946. *Detailed field-by-field accounts of location, development history, geology, reservoir data, recovery methods used.*

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54th Annual Report of the Ontario Department of Mines. Pp. 81. Ontario Dept. Mines Annual Rep., vol. 54, part 1, 1945. Toronto, 1947. *Statistical review of Ontario mineral industry, list of quarries and works for structural materials and clay products, 1944.*

Geology of Township 47, Missinaibi Area. E. L. BRUCE. Pp. 24; figs. 4; map (colored). Ontario Dept. Mines Annual Report for 1945, Vol. LIV, Part IV. Toronto, 1947. *Minor Au-quartz mineralization along shears in Precambrian greenstones and intrusives.*

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Bulletins of the "Comite Directivo para la Investigación de los Recursos Minerales de Mexico," Mexico, D. F.

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No. 3 (1946). Los Yacimientos de Tungsteno en la Parte Sur del Estado de Sonora. J. H. WIESE. SALVADOR CARDENAS. Pp. 48; figs. 3; pls. 6; tbl. 1. *Tungsten deposits within 150 miles of Hermosillo, Mexico. Reserves 12,600 tons approx. 2% WO_3 mostly in contact metamorphic deposits, some in pegmatite dikes and quartz veins.*

No. 4. La Industria Minera en el Estado de Zacatecas. JENARO GONZALEZ R. Pp. 127. *Report on general economic conditions, geology, production, reserves in the state of Zacatecas, Mexico. Important producer of Au, Ag, Pb, Zn, Cu, Hg.*

No. 5 (1946). Los Criaderos de Uranio y Oro en Placer de Guadalupe y Puerto del Aire, Estado de Chihuahua. JENARO, GONZALEZ R. Pp. 27; photos 8. *Low-temperature gold and uraninite-after-pyrite with calcite, quartz in narrow vein fillings in Cretaceous rocks. Mineralization from andesite porphyry. Extensive placers. Reserves not estimated.*

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No. 9 (1946). Los Yacimientos de Carbón de la Region de Santa Clara, Municipio de San Javier, Estado de Sonora. I. F. WILSON, V. S. ROCHA. Pp. 108; figs. 8; pls. 8; tbls. 9. *Low-grade anthracite to meta-anthracite coal in 1 to 2 meter seams in Barranca formation of Upper Triassic and Lower Jurassic (?). Reserves 30,000 tons measured; 230,000 indicated; 2,000,000 inferred; 4,000,000 possible.*

No. 10 (1946). Los Depósitos de Magnesita de la Porción Central de Isla Margarita, Baja California. JENARO GONZALEZ R. Pp. 31; photos 18; map 1. *Irregular veins and masses of cryptocrystalline magnesite in serpentinized peridotite and pyroxenite on Margarita Island off W. Coast of Lower California, Mexico. Reserves 320,000 tons.*

No. 11 (1947). Los Yacimientos Argentíferos de Batopilas, Estado de Chihuahua (Informe Preliminar). JENARO GONZALEZ R. Pp. 24. *Preliminary report on old silver district of Batopilas, Chihuahua, Mexico. Low temperature fissure fillings of native silver, pyrite, galena, sphalerite, ruby silvers in basic intrusives.*

SOCIETY OF ECONOMIC GEOLOGISTS

Abstracts of papers presented at the Twenty-seventh Annual Meeting, in conjunction with the American Institute of Mining and Metallurgical Engineers, New York, March 19–21, 1947.

GEOLOGY AND GROUND-WATER RESOURCES OF PUERTO RICO.[1]

C. L. MCGUINNESS.

Puerto Rico, the easternmost and smallest of the Greater Antilles, has an axis of deformed and metamorphosed volcanic rocks of Upper Cretaceous age, intruded by dioritic rocks during the Antillean revolution. The hard-rock core is flanked on the north and south by limestones and clastic rocks of late Oligocene and early Miocene age, which have been gently arched and uplifted. Similar rocks were deposited in late Miocene or early Pliocene time along the west coast. During the Quaternary the island has been separated from the other major Antillean islands by faulting and has been arched, uplifted, and tilted to the northeast. Alluvium and littoral deposits have partially filled the valleys and have formed coastal plains on the north and south.

The Upper Cretaceous volcanic and associated rocks yield small supplies of water to wells in most places. The Tertiary limestones yield large supplies in some places on the north, south, and west coasts. The Quaternary sands and gravels are the most important aquifers. They yield about 200 million gallons a day to wells in the main south coastal plain alone. The water is used largely for irrigation. A total of perhaps 250 to 300 million gallons a day is pumped from wells in the island, and moderate to large additional supplies are available in some places.

[1] Published by permission of the Director of the Geological Survey, United States Department of the Interior.

SOME SOLUTIONAL FEATURES OF THE LIMESTONE NEAR LEXINGTON, KENTUCKY.[1]

D. K. HAMILTON.

Field work on the Ordovician limestones and shales of the Lexington area, Kentucky, has shown that no appreciable quantity of ground water is transmitted through interstitial openings in these rocks. Ground-water movement is restricted to joint and—to a lesser extent—bedding planes, which have been enlarged by solution. Studies of these planes indicate that solution has been effective only to a limited depth below the land surface. The bottom of the solutional zone is an exaggerated replica of the land surface, showing a greater depth of the solutional zone below stream valleys. The greater depth is attributed to the greater accumulation of ground water, the dissolving agent, in those areas. Modifications of the ideal condition are effected by the less soluble beds and by the configuration of the land surface.

[1] Published by permission of the Director of the Geological Survey, United States Department of the Interior.

The underground drainage systems of the area develop in a manner similar to rectilinear stream patterns, showing a definite alignment along the two sets of joints of the area. Directional solution has taken place where one of these sets of joints has been developed to the exclusion of the other.

GROUND-WATER INVESTIGATIONS IN THE IRON RIVER MINING DISTRICT, MICHIGAN.[1]

CHARLES V. THEIS AND WILBUR T. STUART.

The U. S. Geological Survey, in cooperation with the Michigan Geological Survey, has been conducting a study of mine drainage problems in this district, primarily to explore the possibility that ground-water techniques may help in the solution of these problems.

The iron-bearing formation in this district is permeable and lies in sharply contorted troughs beneath a cover of glacial drift from a few feet to a few hundred feet thick. Water fed by penetration of rainfall and by leakage from streams moves through the glacial overburden down buried bedrock hillsides to collect to a depth of 200 feet or more in the bedrock valleys, thence to discharge under natural conditions into surface waters. Where the iron-bearing formation crops out beneath the thick bodies of ground water, large quantities move through the formation to nearby mines. The design of feasible water-control measures requires a good understanding of the ground-water circulation.

Methods of investigation have included the usual geological methods of study of the bedrock geology, the topography of the buried bedrock surface, and the character and thickness of the glacial drift. Pumping tests of wells and water-level measurements have been made to learn the hydraulic characteristics of the drift, and the theory of circulation in the steeply-inclined aquifer has been studied. Theoretical diagrams and formulas are given for the rate of flow and the distribution of pressure and hydraulic potential in the formation and the glacial drift under several conditions.

[1] Published by permission of the Director of the Geological Survey, United States Department of the Interior.

THE LOCATION OF BULL SHOALS DAM.

GEORGE D. ROBERTS.

The foundation investigations, and the theory on the weathering of limestone, which led to the selection of the Bull Shoals dam site are reviewed. The U. S. Engineer Department recently awarded a $24,263,935 construction contract for this dual purpose dam in northern Arkansas. It will contain about 2,090,000 cubic yards of concrete and will provide 5,408,000 acre-feet of reservoir storage. Close cooperation between the engineers and geologists resulted in locating a good site for this important dam after several previous attempts failed. The potentialities of a dam in this region, which has 6,036 square miles of drainage area and an average annual stream flow of 6,190 c.f.s., have long been recognized. In 1938 consulting engineers reviewed the results of a previous foundation investigation, made by several power companies at a cost of about $1,000,000, and concluded that the project was not feasible because of the high costs and the uncertainties relative to treating the cavernous limestone foundations. Subsequent geologic studies in the limestone areas of the Ozarks developed an apparent relationship between the topography of entrenched streams and the weathering of limestone. This led to the selection of a new dam site in 1939. This site had identical beds of dolomitic limestone and a geologic structure similar to the unsatisfactory sites previously investigated. However, the estimated cost of foundation treatment was a half-million dollars in contrast with the former estimates ranging from four to twenty-seven million dollars at the best site previously considered.

METHODS AND OBJECTIVES IN ENGINEERING GEOLOGY IN THE TENNESSEE VALLEY AUTHORITY.

BERLEN C. MONEYMAKER.

The construction of 18 large dams in the Tennessee Valley by the Tennessee Valley Authority has required a very large amount of geologic work, nearly all of which has been done by the Authority's own highly specialized staff of engineering geologists. The geologic organization is charged exclusively with geologic work. All operating activities, such as exploratory drilling, test-pitting and trenching, are carried on by engineering personnel, but the results of these operations are interpreted by geologists. Similarly, all work in soil mechanics, geophysics, materials testing and related sciences are left to specialists in these fields.

The geologic investigation of a TVA dam site falls into three stages which may overlap to some extent. These stages are:

1. *Preliminary Investigation*—A geologic field party makes a very detailed investigation of the entire section of the river under consideration. This investigation includes studies of the stratigraphy, geologic structure and physiography of the area as a whole, and bedrock conditions and the thickness and character of the overburden at tentatively selected dam sites. The area is mapped geologically on the scale of 1 in. to 500 feet to show the various types of rock, contacts, faults and joint patterns. Throughout this stage, very close cooperation is maintained between the geologists and the planning engineers so that the site that best meets all requirements may be selected for exploration.

2. *Exploration*—In the exploration stage the geologic studies involve the development of the details of structure, lithology, and rock conditions. By means of drill holes, trenches, pits, and tunnels, the configuration of the top of rock, the thickness and character of the overburden, and the extent of rock decay and solution are determined. Numerous geologic sections are drawn to show in as much detail as possible the structure, lithologic units, cavities, and zones of rock decay along various ranges. Very close cooperation between the geologists and the engineers is continued throughout the exploratory stage.

3. *Construction*—A geologic field party is maintained at each project throughout the construction period. In this stage, hundreds of detailed drawings are made, showing in detail all the geologic features that have any bearing upon engineering problems. These drawings, supplemented by numerous daily conferences, keep the engineers informed in advance of all conditions to be met. In no stage of a project is the geologist more useful than in the construction stage.

MINERAL INVESTIGATIONS IN TVA RESERVOIRS.

BERLEN C. MONEYMAKER.

The acquisition of a large reservoir area by the Tennessee Valley Authority necessitates the investigation of numerous alleged mineral deposits. These investigations are necessitated by (1) active claims by the owner that certain tracts contain minerals of value which the Authority should pay for, (2) mineral interests or mining rights outstanding in third parties, by reason of purchase, and (3) "mineral rights" or "mineral interests" reserved in previous deeds by original owners and their heirs. A field examination is made of each tract on which mineral claims or mineral rights are involved, and an appraisal report is prepared for the guidance of the land buyers. In some reservoirs, especially where the people are mineral conscious to a high degree, a very large percentage of the tracts must be examined. In nearly all cases the field examination and appraisal are sufficient to satisfy the interested parties, but a few active claims become court cases. In such cases more detailed work and the presentation of testimony in court are required.

In a reservoir where numerous mineral claims are anticipated, much time is saved by the preparation of a geologic map of the reservoir in advance of the investigations. A geologic map shows not only the formations that are present, but also the location and extent of ore bodies and structural and stratigraphic zones in which mineral deposits may be expected to occur.

THE EASTERN PART (MALARTIC TO PERSHING) OF THE KIRKLAND–VAL D'OR BREAK.

G. W. H. NORMAN.

Field studies since 1931 have shown the continuity of structure from Noranda eastward to, and beyond, Val d'Or and the probable extension westward through the Larder and Kirkland camps. Ore deposits (mostly gold but locally important copper and zinc) are restricted to a comparatively narrow belt along this great structure for about 160 miles. A great strike fault, which plays a pre-eminent role in the structure of the central and western sections of the belt, becomes one of a series of fault and fold structures in the eastern part. A possible explanation for the more complex structure of the eastern part may be the confluence of Kirkland-Larder-Noranda and the Porcupine structural belts near Malartic township and their continuation eastward therefrom as one large belt. The complexity is enhanced by the presence of lenticular bodies of much altered peridotite that play an important role, locally, in relation to vein structures in the eastern part, but are lacking in the central and western sections of the belt. Gold has been produced in the eastern section continuously since 1929, and zinc, silver and a small amount of lead since 1943.

STRUCTURE AND ORE DEPOSITS OF THE KIRKLAND LAKE, NORANDA, VAL D'OR REGION, ONTARIO AND QUEBEC (WESTERN OR ONTARIO SECTION).

JAMES E. THOMSON.

The Ontario Section of this important mineral belt extends westward from the Quebec boundary for at least 35 miles and may continue much farther under cover of later formations. It includes the Kirkland Lake and Larder Lake mining camps which, to date, have produced more than half a billion dollars worth of gold. The mineral-bearing rocks consist of an early Precambrian complex of volcanics, sediments, and intrusives. These are generally closely folded and intricately faulted. A regional strike fault is believed to extend across the entire belt and the structural disturbances within its sphere of influence are thought to have a bearing on the localization of the ore deposits. Structure is believed to be much more important than rock types in ore localization. There are several periods of pre-ore and post-ore faulting.

STRUCTURE AND ORE DEPOSITS OF THE KIRKLAND LAKE, NORANDA, VAL D'OR BELT, ONTARIO AND QUEBEC.

M. E. WILSON

The territory extending from Kirkland Lake, Ontario eastward to Louvicourt township, Quebec, includes numerous mines, some of which are among the most important in the Canadian pre-Cambrian Shield. The production of gold, copper, zinc, and other metals from this zone since 1912 in Ontario and 1927 in Quebec has had a total value of over $1,000,000,000.

Except for some ridges of (Huronian) Cobalt series and dikes of diabase of Late pre-Cambrian age, the bedrock formations of the region belong to the Archean and have been highly folded and are traversed by numerous faults most of which

are of the overthrust type. Nearly all the faults are marked by zones of schistosity and intense alteration to carbonate, chlorite and talc.

In the middle section of the zone the Archean rocks are volcanics, and clastic sediments that have been invaded by diorite, granite, and other igneous intrusives. All of the ore deposits are associated with faults or drag folds related to faults. The two most important faults are the Horne Creek and the Cadillac-Bouzan Lake. The last except for one interruption extends continuously across the region to near the Ontario boundary where it disappears beneath the Late pre-Cambrian Cobalt series. It is probably continuous with a similar fault described by Thomson in the Kirkland Lake-Larder Lake area. The ore deposits associated with the Horne Creek fault are of the copper-gold type whereas those so far discovered adjacent to the Cadillac-Bouzan Lake fault are gold-bearing only.

A METALLURGICAL INTERPRETATION OF ORE GENESIS—AN ALTERNATIVE TO THE HYDROTHERMAL THEORY.

JOHN S. BROWN.

The hydrothermal theory is questioned from many angles, and a geological and chemical basis suggested for its drastic revision. Support for this proposition is drawn from two sources, (1) mineral paragenesis and (2) zoning, supplemented by data from metallurgical experience.

Paragenesis, it is pointed out, seems to be related closely to specific gravity; lighter substances usually arrive first and heavier ones later. This implies gravity stratification in the source as a controlling factor. The existing concept of a single source magma, in any one locality, for all the elements in ore deposition is considered incongruous. Metallurgical principles indicate separate sources for silicates (pegmatites), oxides (iron ores) and sulphides (including arsenides, antimonides and precious metals). Paragenesis implies that these occur progressively deeper. The first two types probably are localized and somewhat variable but the latter very likely is widespread, perhaps continental in extent, constituting a stratum resting on a crystalline peridotite floor at a depth of between 25 and 50 miles.

Zoning is not a function of the solubility of mineral substances. On the contrary, evidence is presented relating it strictly to their inherent volatility. This indicates that they travel principally under their own power, as vapor, not in solution. As these vapors approach the surface they encounter water in increasing volume, and its influence on deposition is admitted to be often predominant, especially in epithermal deposits, and perhaps always essential, but rather as a precipitant and a medium of dispersal for gangue, than as a transporting agent.

FACTORS IN THE DEPOSITION OF HYDROTHERMAL ORES.

CARLTON D. HULIN.

Available evidence indicates that to produce the ore deposits of an important mining district, some tens of cubic miles of mineralizing solutions must have been actively involved, the action extending over a lengthy period of time. The solutions ascend at elevated temperatures, temperatures below the critical temperature of water (374° C.) but above the surface boiling point (100° C.) being generally agreed upon.

During the earliest stages of mineralization the hydrothermal solutions would be chilled by loss of heat to the wall rocks. Before the mineralization is far advanced, however, the wall rocks will have become heated, a condition approximating temperature equilibrium between the mineralizing solutions and the wall rocks would be attained, and elevated temperatures would prevail in the column of solution all the way to the surface.

It necessarily follows that once this approximation of temperature equilibrium between the column of mineralizing solution and the enclosing wall rock is attained, the solutions *at some point in their ascent must start boiling.*

Once boiling is initiated, the extraction of latent heat of vaporization would lead to an ever-increasing steepness of the temperature gradient as the solutions ascend, with consequent accentuated deposition of mineral substance. Concurrently the formation of gas phase (steam) by boiling results in continuous acceleration in the velocity of ascent of the solutions. Ultimately, with continued boiling as the surface is aproached, the mineralizing fluid will approximate the condition of wet steam traveling at high velocity. Manifestly, under these latter conditions in the zone near the surface, deposition of mineral substance is prohibited.

The boiling mechanism explains not only the bonanza deposition which characterizes the epithermal zone, but also the deposition in underlying zones at least as deep as the mesothermal. It also explains the barren zone which overlies the productive horizon of all epithermal deposits other than quicksilver.

Controlled by a number of inter-dependent variables, the complexity of the boiling mechanism is obvious. Recognition of the possible variations which may occur in the dimensions and conditions within the boiling zone destroys the validity of the concept of the "ideal vein" with its fixed succession of zones of metal deposition which has been so commonly postulated in the literature of zoning.

RESEARCH ON GEOCHEMICAL PROSPECTING BY THE GEOLOGICAL SURVEY.

H. E. HAWKES, JR.

The Geological Survey has undertaken a program of research on new methods of prospecting for mineral deposits, based on studies of the geochemical dispersal of minor elements derived by the leaching of buried mineral deposits. Particular emphasis is being placed on the content of zinc, copper, and lead in soil, vegetation, and natural water, and its relation to known or suspected bodies of ore.

Considerable data on the distribution of these elements in surface materials have already been collected by agricultural scientists in their studies of inorganic plant poisons and fertilizers. Their work gives the geologist a broad background of analytical techniques and preliminary geochemical information which can be applied with little modification or reinterpretation to prospecting problems.

Several geochemical field studies are currently in progress, and preliminary results are believed to be sufficiently encouraging to warrant further and more intensive study. The ultimate goal of the Geological Survey's program is the development of a routine method by which a relatively untrained field party will be able to prospect for hidden mineral deposits by tracing the distribution of minor elements in surface materials.

THE SEARCH FOR ORE DEPOSITS—GEOLOGIC METHODS AND CONCEPTS.

FRED M. CHACE.

Geology is the basic skill in the search for ore deposits and must be used more extensively and with more acumen if many new ore bodies and mining districts are to be found to replace those depleted by extensive mining during recent years, and if the "have-not" hypothesis is to be successfully challenged. The present paper summarizes geologic methods and concepts that are useful in the search for ore. In general, two lines of attack may be followed: (1) the search for ore in known districts, and (2) the search for new districts.

In known districts the search should be based on a detailed geological and historical knowledge of the mineralized area, and all possible structural, miner-

alogical and theoretical concepts and guides to ore should be developed and used. With these as a background, attention can be given to (a) Extensions of known ore bodies, (b) Repetitions of known ore bodies, (c) New ore bodies of previously unrecognized structural control, (d) Extensions of known districts.

The search for new districts should be based on a knowledge of regional geology. Two methods of approach are followed, (a) search for a specific metal or mineral, and (b) investigation of a specific area. In either case the following geologic concepts may be useful: (a) Metallogenetic provinces, (b) Distribution of ore deposits with respect to batholiths and stocks, (c) Relation of ore deposits to regional structure, (d) Physiography as a guide to ore, (e) Rock alteration, (f) Physical and chemical properties of rocks.

THE SEARCH FOR CONCEALED DEPOSITS—A REORIENTATION OF PHILOSOPHY.[1]

SAMUEL G. LASKY.

This paper enlarges upon a statement, previously published by the author, that if the search for concealed deposits is to be notably successful there must be, among other things, a reorientation of philosophy and mental habits on the part of many connected with the search.

In appraising a deposit or district, the examiner, instead of looking only for information indicating that ore is likely to be present, should deliberately attempt to balance and fit together the observed facts so as to discern whether ore could be present. In the stage of work involving geologic mapping, the geologist should be consciously alert to the purpose of his work and its practical implications. He should be deliberately optimistic and speculative, though balancing speculation by rigid scrutiny of evidence and accepted theory. When geologic maps are used by someone other than the maker in considering the favorability of an area, it should be remembered that a geologic map is as much a product of geologic art as of geologic science; it bespeaks not only the skill and experience of the maker, but also his opportunities, his specialty, his temperament, and his purpose.

Finally, in the financing stage of exploration, it would further the likelihood of successful search if management accepts the skilled judgment of the geologic staff as to the gamble involved and, while retaining the right to decide what return on the investment and what assurance of return would be satisfactory, be more liberal in what it is willing to accept as satisfactory.

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STRUCTURAL CONTROL AND WALL-ROCK ALTERATION AT THE WILBERT MINE, BUTTE COUNTY, IDAHO.

ALFRED L. ANDERSON.

The ore at the Wilbert mine in Butte County, Idaho, consists largely of fine-grained galena deposited mainly by replacement of a dolomitic member in a thick series of complexly folded and faulted Ordovician quartzites. Much of the ore from the surface to the 600 level has been localized along a curved, southwestward-dipping thrust fault. From the 600 to the 1,450 levels the ore follows the northeastward-dipping contact between dolomite and the overlying quartzite, forming an irregular, somewhat pipe-like body that pitches steeply at first and then assumes a horizontal position, which is maintained to the present working face 1,000 feet to the north. Ore along the contact apparently has been localized by a minor structural crease transverse and in part parallel to the strike of the beds.

Mineralization was accompanied by marked alteration of the dolomite, which in the ore zone in the deepest part of the mine was changed to a feldspathic rock resembling porphyritic granite. This "granitized" dolomite was then further altered

and the feldspars largely replaced by pseudomorphous carbonates and silica. The successive stages of alteration were (1) sodic plagioclase-microcline stage, (2) carbonate (dolomite-calcite) stage, (3) jasperoid and quartz stage, and (4) scant sericite stage. Sulphides then introduced included the galena and very small amounts of pyrite and sphalerite.

The best guide to ore in the deeper workings of the mine is the zone of "granitized" dolomite.

THE BEDDING REPLACEMENT FLUORSPAR DEPOSITS OF SPAR VALLEY, EAGLE MOUNTAINS, TEXAS.

ELLIOT GILLERMAN.

The Spar Valley fluorspar district in the Eagle Mountains, Hudspeth County, Texas, is one of the few in western United States containing bedding replacement fluorspar deposits. The deposits at Spar Valley most closely resemble the bedding replacement deposits of the Cave in Rock fluorspar district of southern Illinois. Two distinct bedding replacement fluorspar deposits at Spar Valley are called the North ore body and the South ore body. The North ore body is larger and has been developed by diamond drilling and mining; the following statements apply chiefly to it.

The fluorspar partly replaces a sequence of three sandy limestones interbedded with four calcareous shales in the lower part of the Edwards limestone of Lower Cretaceous age. The fluoritized beds, which dip 40° SW. in conformity with underlying limestone, are overlain by thick impermeable gouge along a bedding-plane fault dipping slightly more than 40° SW. The high-grade beds were derived from the sandy limestones, and the low-grade beds, which contain as much as 28 per cent of CaF_2, were formed from the calcareous shales. The selectiveness of replacement by the fluorine-bearing solutions, due to differences in the chemical composition, texture, and degree of brecciation of the original rock, resulted in bedding replacement deposits of variable fluorite content.

A reduction in volume, which accompanied the replacement, led to the development of many cavities. At a later stage of fluoritization these cavities were lined with fluorite crystals, early fluorite grains were coated and interstices between them were filled, and fluorite veins were formed in the ore beds and the underlying dense limestone.

APPLIED GEOLOGY AT THE MAGMA MINE, SUPERIOR, ARIZONA.

WILSON D. MICHELL.

The Margma copper vein trends east-west, dips 70° south, and cuts through a 6,000 foot thickness of limestones, quartzites, shale, diabase, and schist. The vein is itself a fault, with a horizontal offset of 500 feet on the formation contacts in the two walls. There are two principal strike faults of large displacement, and numerous smaller steep and flat faults that complicate the prediction of ore occurrence. A study of the geology, its systematic recording to facilitate ready reference, and graphic methods of interpretation of mineralization have aided the exploration, development, and mining of the ore. It has been found possible to make reasonably accurate prediction of the distribution of mineable ore bodies and their shape in critical areas by studies of "mineralization contours" and "mineralization trends," which are developed on a longitudinal section of the vein by showing variations in the concentration of the combined base metal content, weighted as to the widths of the values across the vein.

STRUCTURAL CONTROL OF FLUORSPAR DEPOSITS IN THE ZUNI MOUNTAINS, NEW MEXICO.[1]

E. N. GODDARD.

The Zuni Mountains consist of a broad, highly dissected domal uplift of Permian sediments extending from the vicinity of Gallup, N. Mex., southeastward for about 50 miles. In places a pre-Cambrian core of gneissic granite, aplite and metarhyolite is exposed. The fluorspar deposits are confined to a large area of these pre-Cambrian rocks in the southeastern part of the mountains. Strong, steeply dipping, northwestward-trending faults border this pre-Cambrian area and also cut diagonally across it. On most of these faults the southwest side has moved up, and the pre-Cambrian blocks have been raised and slightly tilted toward the southwest. This fault pattern is strikingly similar to that of the breccia reef faults in the Colorado Front Range, and the faults in both regions are marked by the same type of brecciation, shearing, silicification and red hematitic coloration.

The fluorspar deposits form steeply dipping, northeastward-trending veins, which range from a few hundred to 5,000 feet in length. All the fluorspar veins are in close proximity to the northwestward-trending faults, and the two most productive veins intersect one of these faults. In places small amounts of fluorspar are found in the northwestward-trending faults, but these strong shear zones were mostly too tight for fluorspar deposition. It is believed that these strong faults served as trunk channels along which the fluorine-bearing solutions rose from depth and then spread out into the more open northeastward-trending vein fissures.

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GEOLOGY OF THE BATUCO LEAD–ZINC DEPOSITS IN CENTRAL CHILE.[1]

JAMES F. MCALLISTER AND VINCENT E. SHAININ.

The Batuco lead-zinc deposits, 25 kilometers northwest of Santiago, Chile, formed within fractured zones in Mesozoic andesitic tuff, breccia, and intercalated flows, which lie on massive andesite agglomerate in the northwest and on platy felsitic andesite in the southeast. The relation to ore of minor basalt porphyry and diorite intrusions is unknown. The stratified rocks in general form a gently dipping homocline, cut by faults of apparently small displacement. Faulting preceded and followed mineralization, and was its chief structural control.

Galena and sphalerite, associated with quartz, calcite, chalcopyrite, and pyrite, occur as fissure fillings and replacements. The abundant quartz started forming earlier, often in comb and cockade structures. Sphalerite weathered more readily than galena and was completely leached from outcrops.

Relatively small ore shoots occur in a quartz lode that dips from 55° to vertical. It is roughly 3 meters thick and is exposed intermittently for at least 3 kilometers and over a vertical distance of 400 meters. The lode contains at least traces of ore minerals throughout its length. Average samples from one ore shoot assayed 10 to 15 per cent lead, and 15 to 20 per cent zinc; average samples from another assayed 2 to 3 per cent lead, and 10 to 15 per cent zinc. The well-known Desengaño mine, on the same lode, was worked for copper within the last century.

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ZONED MAGNETITE-BEARING PEGMATITES IN CENTRAL CHILE.

VINCENT E. SHAININ.

Magnetite-bearing pegmatites, possessing distinct zonal structures, occur in coarse-grained biotite-granite on the Pacific coast of South America at Quintero,

Chile. Magnetite does not occur in commercial quantities, but the mode of occurrence suggests formation of the mineral at lower temperatures than usual.

The typical Chilean pegmatite is a lens 2 to 20 feet long. The minerals are grouped in concentric zones of contrasting composition and texture that occur in the following order from the walls inward: (1) narrow border zone of fine-grained plagioclase and quartz; (2) thick zone of medium-grained graphic-granite, perthite, quartz, plagioclase and minor amounts of magnetite; (3) core of coarse-grained quartz and perthite with minor albite, muscovite and magnetite; the perthite occurs in scattered subhedral crystals, many surrounded by rims of albite.

The mineral-relations suggest formation of the essential minerals of the zones by successive deposition from the walls inward. Some accessory magnetite also formed in this stage. Later, soda-rich hydrothermal solutions gained access to the contacts between faces of coarse subhedral perthite and anhedral quartz in the core. The perthite was replaced inward from the crystal faces by albite, magnetite and muscovite. All of the magnetite observed is anhedral. Small solution cavities, lined with silvery muscovite euhedra, are common in the albite.

ORIGIN OF GOLD PLACERS IN NORTHERN TIERRA DEL FUEGO.[1]

VINCENT E. SHAININ.

Hillside and valley gold placers in the Rio del Oro region of Tierra del Fuego have been exploited for more than 50 years. The hillside placers, which yielded 0.66 gram per cubic meter, have been almost exhausted, but large tonnages of lower grade gravels still appear to lie in the valley of Rio del Oro.

The placers are at least third generation deposits. Primary gold, from the Cordillera of western Tierra del Fuego, was transported eastward by Pleistocene glaciers and deposited in moraines. Recent stream action concentrated the gold in the valleys of Rio del Oro and other main streams.

Gravel counts were made for the Corporación de Fomento de la Producción in two areas of the valley of Rio del Oro in an effort to determine more closely the origin of the gold. Thirty-nine per cent of the gravels studied (and more than half of their igneous and metamorphic constituents) were apparently derived from rhyolitic and granitic areas of relatively small extent in, and north of, the Cordillera Darwin in western Tierra del Fuego. The gold, as well, may have been derived from the same areas.

Other constituents of the gravels are: sedimentary rocks, 23 per cent, derived from the Cretaceous and Tertiary beds northeast of the Cordillera; metamorphic rocks, 22 per cent, from extensive areas of metamorphics in western Tierra del Fuego; and basic igneous rocks, 16 per cent (chiefly basalt and gabbro), derived from dikes and small intrusives in western Tierra del Fuego.

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PETROGRAPHIC FEATURES OF SHEET MUSCOVITE IN SOUTHEASTERN UNITED STATES AS RELATED TO COMMERCIAL CLASSIFICATIONS.[1]

RICHARD H. JAHNS.

The need for reliable correlation between physical properties and commercial grading of sheet muscovite is becoming increasingly apparent. Grading based on color, stain, mechanical inperfections, filming characteristics, and other features is being supplemented by tests for dielectric strength, power factor, and freedom from conducting impurities. According to the American Society for Testing

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Materials these electrical characteristics, together with such other features as air stain, waviness, cracks, tears, pinholes, "stony" inclusions, reeves, and buckles, are important in establishing a satisfactory commercial classification. Tests have demonstrated the intrinsically high quality of much mica hitherto regarded as distinctly inferior on the basis of visual examination alone.

Electrical tests of sheet muscovite from the Southeastern States have been made by the U. S. Bureau of Standards, the U. S. Geological Survey, and jointly by the Geological Survey, the State of North Carolina, and the Tennessee Valley Authority. These tests have shown that neither the color nor the depth of color in clear material has any definite relation to its power factor. Moreover, much mica that contains inclusions and intergrowths of iron oxides has a low power factor, whereas some clear and nearly clear sheets have moderate to high power factors. In general, however, muscovite that contains substantial quantities of iron—either as inclusions, exsolved intergrowths, or in solid solution—has less desirable electrical properties than iron-poor varieties.

Wispy to platy inclusions of green and brown biotite appear to have little effect on the power factor of muscovite, although some do impair its splitting properties. Similar relations also apply to much green mottling, "vegetable stain," and other finely divided impurities. Some Southeastern mica classed as top quality by visual means actually is not suited for exacting end uses, owing to the presence of tiny pinholes. Most of these holes are developed from the popping out of zircon, quartz, and apatite inclusions.

Adoption of the new combined visual–electrical system of mica classification should result in upward grading of much sheet material from the Southeastern States, and might well improve the currently inferior position of the abundant green and dark brown varieties in the trade.

THE TALC DEPOSITS OF THE GOUVERNEUR DISTRICT, NEW YORK.

ALBERT E. J. ENGEL.

The talc deposits of the Gouverneur district, which are the largest and most productive in North America, are in the northwest Adirondack Mountains, New York. The talc occurs in elongate zones interlayered within a northeastward-trending belt of impure marble of the Pre-Cambrian Grenville series.

The marble belt is apparently part of a highly deformed and metamorphosed flank of a northeastward-trending anticline. Cross folds, plunging north to northwest, foliations, shears, and lineations constitute important structural features of the talc zones.

The zones of commercial talc pinch and swell, and curve in sinuous to complexly folded patterns, but are rudely conformable with adjoining marble layers. The talc zones have a composite strike length of more than 5 miles, a probable extent down dip in excess of 2,000 feet, and widths of as much as 400 feet.

Most of the rock mined is composed of fibrous tremolite, serpentine and talc. The tremolite was formed largely during severe stages of dynamothermal metamorphism, whereas most of the talc and serpentine developed during the final stages as fibrous pseudomorphs after tremolite.

Much of the tremolite probably formed by reactions between, and replacement of, physically and chemically favorable beds of quartzite and dolomite. This initial stratigraphic control of talc distribution was partly obscured, and to some extent superseded, by prominent secondary structures, especially shear zones that developed during metamorphism.

The talc-forming constituents were derived largely from the quartzite and dolomite beds, but water, silica, and possibly some magnesia were introduced and calcite removed by hydrothermal solutions.

In 1946 six mines and six mills were active, producing ground, fibrous talc at the annual rate of about 120,000 tons.

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PENNSYLVANIAN CLAY HORIZONS OF WESTERN MARYLAND.[1]

KARL M. WAAGE.

Clay seams in the Pennsylvanian strata between the base of the Pottsville and the middle of the Conemaugh series were studied in the Georges Creek, Upper Potomac, and Castleman basins of Maryland. Information on the clays was gathered by the Geological Survey in cooperation with the Federal Bureau of Mines and the Maryland Board of Natural Resources.

Correlation of core drill records and surface sections indicates that lithologic units between the base of the Pottsville and the Middle Kittanning coal are not persistent. Most of the commercial refractory flint clays are in this interval where local deposition and erosion of clay have been responsible for the limited extent and unpredictable occurrence of clay bodies.

In the stratigraphic interval between the Middle Kittanning and Brush Creek coals the stratigraphic units are fairly continuous. Soft to semi-hard underclays commonly contain silt and sand. Hard clays are chiefly fragmental claystones which locally grade into fragmental flint clay. Introduction of impurities by reworking during and shortly after deposition has resulted in few clay bodies of commercial grade.

Within the interval between the Brush Creek coal and the middle of the Conemaugh series the clays are not of refractory grade. Underclays are soft and predominantly calcareous, grading laterally into fresh water limestones. Similar underclays are found throughout the rest of the Conemaugh series.

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APPLICATIONS OF THE CONCEPT OF ZONAL STRUCTURE IN PEGMATITES TO PROSPECTING FOR FELDSPAR.[1]

EUGENE N. CAMERON.

Studies of pegmatites during the intensive wartime search for strategic mica, tantalum, beryl, and other pegmatite minerals have shown that these materials are won largely from zoned pegmatites composed of successive concentric shells having contrasting mineralogy or texture. The forms of the zones reflect, more or less closely, the shapes of the walls of a pegmatite, and zones of various compositions in general occur in regular sequences inward from the walls. Once the sequence of zones has been established for a group of pegmatites, systematic prospecting based on determination of the form of a pegmatite and on knowledge of the possible positions of commercially valuable zones within it is greatly facilitated.

The concept of zonal structure is being applied to the prospecting of pegmatites in several districts in the United States. Applications to the problem of feldspar prospecting will be discussed and illustrated by examples from the Bryson City district of western North Carolina.

[1] Published by permission of the Director, Geological Survey, U. S. Department of the Interior.

THE MAGNESITE DEPOSIT AT GABBS, NEVADA.

CHARLES J. VITALIANO AND EUGENE CALLAGHAN.

During the recent war the replacement magnesite deposit at Gabbs, Nevada, was the source of ore for the largest magnesium metal plant in the United States and possibly in the world. The deposit was formed under deep-seated conditions by the action of magnesian solutions on Upper Triassic dolomite. Some of the dolomite has been recrystallized, and some converted to magnesite. The structural relations between the unreplaced dolomite, recrystallized dolomite, and magnesite

are complex. Relict masses and fragments are abundant. Locally, replacement has followed bedding, but commonly the boundaries between replaced and unreplaced rock are very irregular.

Impurities in the magnesite include CaO in unreplaced dolomite, near-surface caliche, and aragonite and calcite in solution cavities and breccias. Shaly partings and cavity fillings of iron oxide contribute to the R_2O_3 content. Silica occurs in the silicate minerals of which serpentine, talc, and forsterite are the most common. Dike rocks add to the impurities and constitute a problem in quarrying the ore.

MINING AND GEOLOGY STUDIES IN JAPAN.[1]

QUENTIN D. SINGEWALD.

A comprehensive study of mining activities in Japan comprises a part of the integrated work of General MacArthur's staff in Tokyo. This study is being made by the Mining and Geology Division of Natural Resources Section, one of fourteen special staff sections in the General Headquarters. Chief of Natural Resources Section is Lt. Col. Hubert G. Schenck, well-known stratigrapher possessing wide experience in commercial work. Mining and Geology Division consists of four technical branches, with personnel of 55 Americans and 20 Japanese Nationals. Approximately one-half of the technical personnel are derived, on a loan basis, from the Geological Survey and Bureau of Mines.

Basic mining data are procured from all possible Japanese sources, including government agencies, mining companies, and indivdual geologists and engineers. Field trips to mines, mills, smelters, and refineries check and supplement data from Japanese sources. These data, besides serving for day-by-day problems of the Occupation and for overall planning of Japan's future economy, are being made available to the public in Natural Resources Section published reports.

A great increase in mineral production in Japan during the period 1930–45 was accomplished mainly by uneconomic practices, but even so, Japan remained very far from self-sufficient. In the future, Japan is likely to have an exportable surplus of sulfur; to meet, or nearly meet, domestic requirements of coal, water power, pyrite, copper, zinc, chromite, arsenic, clay, limestone, stone, gypsum and dolomite; to produce only a small part of domestic requirements of petroleum, iron, lead, manganese, antimony, mercury, pyrophyllite and silica; and to produce little or no molybdenum, nickel, tin, tungsten, asbestos, barite, fluorspar, graphite, mica and talc.

[1] Published by permission of the Director of the United States Geological Survey.

TUNGSTEN IN JAPAN AND KOREA.[1]

M. R. KLEPPER.

Prior to 1934 Japan and Korea produced and consumed only insignificant quantities of tungsten concentrate but from 1935 until the end of the war both the output and the consumption of concentrate increased tremenduously as shown below:

	Production of 60 per cent WO_3 concentrate (met. tons)		Output of ferrotungsten and other tungsten products (met. tons)	
	Japan	Korea	Japan	Korea
1935	30	300	283	0
Peak year	900[a]	11,500[b]	3,344[c]	3,366[b]
1935–44 tot.	4,500	42,500	19,500	13,220

[a] 1942; [b] 1944; [c] 1943.

[1] Published by permission of the Director, U. S. Geological Survey.

During this same period Japan imported to the Home Islands 17,000 tons of concentrate from sources other than Korea.

In Japan tungsten mining was highly subsidized by the government, and ore was mined from many small, low-grade deposits that could not be mined economically under normal conditions. Some of these deposits were mined out; some contain a small reserve of submarginal ore: a few contain a small reserve of ore that probably can be mined economically.

Korea, in contrast to Japan, has one of the world's outstanding tungsten deposits and several smaller deposits of merit. The outstanding deposit, the Sangdong, was not systematically explored until 1940. Since that time 800,000 tons of scheelite ore have been mined from a calcareous bed that has been altered to tactite and 13,000 tons of concentrate have been recovered. Engineers of the Japanese company that operated the mine estimated that the reserve of ore to a depth of 60 meters below the deepest mine level was about 3,000,000 tons averaging 1.5 per cent WO_3.

Several other tungsten deposits in Korea produced more than 1,000 tons of concentrate during 1940–45. At least two of these contain a reserve of mineable ore.

By 1945 twelve plants in Japan and four in Korea were producing ferrotungsten of standard grade. Total plant capacity in both Japan and Korea was about 3,500 tons of ferrotungsten per year. During the last two years of the war twelve plants in Japan produced tungsten powder, two produced tungsten trioxide, two produced tungsten carbide, and one produced tungsten wire. The maximun output in one year (1944) was 113 tons of powder, 10 tons of trioxide, and a few tons each of carbide and wire.

THE ONGJIN–HAEJU DEPOSIT, SOUTHERN KOREA.[1]

M. R. KLEPPER.

The Ongjin-Haeju deposit in Hwanghae-do has been the largest single source of gold, silver, lead, and zinc in southern Korea since 1937. From 1937 through 1945 the Ongjin Mine, in the southern part of the deposit, produced concentrates that contained 8,301 kg. of gold, 103,036 kg. of silver, 15,549 metric tons of lead, 13,118 metric tons of zinc, and 506 metric tons of copper. During the same period the Haeju Mine, in the northern part of the deposit, produced at least 300 kg. of gold and 17,500 kg. of silver and about 4,900 metric tons of lead. The output of lead from these two mines during 1937–45 was about two-thirds of southern Korea's total, and the output of zinc was about one-third of southern Korea's total.

The Ongjin-Haeju deposit consists of a number of sub-parallel sulphide-bearing quartz fissure veins that cut across a pre-Cambrian metamorphic sequence of argillite, hornfels, quartzite, phyllite, and mica schist. These veins are thought to be genetically related to intrusive masses of late Cretaceous granitic rock that crop out near the mines. The veins are up to 1,750 meters in length and average about 50 centimeters in thickness. Ore mined has averaged about 5 grams of gold per ton, 65 grams of silver per ton, 1.5 per cent lead, 1.5 per cent zinc, and 0.05 per cent copper. Vein thickness and grade of ore have diminished progressively as the depth of mining has increased.

[1] Published by permission of the Director, U. S. Geological Survey.

COAL IN JAPAN–COLLIERY OPERATIONS AND METHODS OF MINING.

KIRK V. CAMMACK.

Present Japanese coal production is secured from fifty-seven relatively small coal fields distributed in the three main islands of Kyushu, Honshu and Hokkaido.

These deposits are of Mesozoic and Tertiary ages and occur in the form of synclinal or monoclinal structures, which are generally badly faulted. Alteration of the coal beds by intrusives has occurred in some fields.

The Tertiary deposits are most important, and the coal beds of that age vary from lignites and high volatile C bituminous coals in the Joban fields of Honshu to high volatile A coking coals in Hokkaido and Kyushu.

Mineral rights are separate from surface rights, and are owned by the government. Practically all coal mining concessions in Japan have been granted to a relatively few companies, who exercise a virtual monopoly on coal production and operate the mines under a system of cost-plus government subsidies.

Individual colliery operations are very extensive, with coal from a number of openings brought to one or more central preparation plants. Wet washing is used in these plants and some of the mines have a 45 per cent washing reject. All the collieries have been made as self-sustaining as possible by the use of small manufacturing plants at the mines, designed to produce those goods necessary for the operation of the mine, and the housing and feeding of the employees. From twelve to fifteen thousand people are employed at one of these large collieries.

A number of workable beds occur at fairly close intervals in each field. Access to these beds is secured through rock slopes supplemented by shaft development. All coal extraction is by long-face methods and accomplished by backfilling, designed to prevent subsidence. Partial packing by hand stowage is generally practiced, although hydraulic and pneumatic stowage systems are in use.

Extensive endless and gravity plane, rope systems are used in haulage, supplemented by belt conveyors on the main slopes. Hand loading at the faces is universal, the coal usually being loaded onto chain or belt conveyors which discharge into pit cars.

Use of cutting machines and explosives in face preparation is limited, the coal being freed from the face by the use of pneumatic picks or hand mining.

Masonry and steel arched timbering is used extensively in development work, the steel used in this timbering having been largely secured in the United States as scrap, prior to the embargo on such material.

Two of the major fields extend beneath the floor of the ocean and drainage is a serious problem in many of the mines. Eighty tons of water is pumped per ton of coal mined in one mine in the Joban Field.

All of the mines are gassy, ventilation being secured by exhaust, centrifugal fans. Direction of the ventilating currents underground is poor and explosions originating in gas ignitions are frequent. These explosions are accompanied by a very high loss of life. Excessive earth temperatures occur in the mines of some of the fields; temperatures of 100° F. being recorded at some working faces.

Two mine experimental stations and a system of governmental inspection, modeled after our state inspection systems, are in operation but are inefficient and and ineffective. Both frequency of accidents and fatality rates per ton of coal produced are approximately 20 times greater than in the United States.

Employment systems at the collieries are largely feudalistic, and the living and working conditions of the Japanese miner are probably the worst in the world. In the war years, employment of Prisoners of War and women labor was universal in all the coal fields, these practices having been terminated by Supreme Commander for the Allied Powers immediately after the occupation.

Comparisons as to mining costs and wages are difficult to make, but in purchasing power of the goods available to him the present wage earnings of the Japanese miner are equivalent to a daily wage of 25 cents per day in the United States. Labor costs comprise about 30 per cent of total production cost. Calculated on an exchange value for goods used, total production costs are comparable to some of the older hand-loading mines of the United States.

Malnutrition and disease are prevalent among the Japanese miners. A current unrest exists against their employers and their conditions of employment. Reaction to American occupation by the Japanese miner and the immediate supervisory officials at the collieries has been very good.

HYDROELECTRIC POWER DEVELOPMENT IN JAPAN.

FRANCIS M. BELL AND MELVIN R. WILLIAMS.

The drainage pattern of each of the four main islands of Japan is made up of hundreds of surface streams having small drainage areas, steep profiles and dependable water supplies. These streams, therefore, are particularly suitable for development as sources of industrial and domestic power.

At the end of 1945 as a result of intensive and extensive development of the country's water resources there were in Japan 1493 hydroelectric plants ranging in size from 75 kw. to 165,000 kw. The combined licensed capacity of those developments was 6,154,185 kw. and the effective capacity for primary power was 3,700,000 kw. In a normal year water power accounts for 75 per cent of total power production.

Because of steep stream profiles and the need for agricultural land, there have been few attempts to develop storage to supplement dry weather stream flow. Accordingly, the typical hydroelectric development is a "run of the river" plant which depends entirely on the natural flow of the stream on which it is located. Fear of earthquake damage has prevented the construction of high dams so that head is generally developed by canals or flumes rather than by dams.

Prior to the war the development of hydroelectric power was entirely by private enterprise, although the government encouraged such development and exercised limited supervision of operations. An outstanding aid to private development were the three extensive water power surveys conducted by the government. In those surveys, intensive studies were made at every suitable power site. Licenses for individual plants were based on data obtained from those surveys. During the war years the government assumed complete control of the generation and distribution of electricity. By such action it was possible to improve efficiency and also to divert large blocks of domestic power to industrial projects.

It is estimated that 57 per cent of the water power potential has been developed and that the remaining 43 per cent is capable of producing 24 billion kwh. in a normal year. However, the best and most accessible sites have already been developed. Additional development will undoubtedly be required if there is any material increase in the Japanese standard of living.

GRAPHITE DEPOSITS OF SOUTHERN KOREA.[1]

W. C. OVERSTREET.

Korea has been the world's leading producer of graphite. From 1925 through 1944 Korea produced more than 937,000 metric tons of graphite worth $21,600,000. Most of this was amorphous graphite; only 12 per cent was crystalline graphite. Most Korean graphite was exported to Japan. From 1925 through 1938 Korea exported 2.2 times as much graphite as Ceylon and 2.6 times as much graphite as Madagascar.

Graphite is widely distributed throughout Korea. About 55 per cent of the amorphous graphite and 5 per cent of the crystalline graphite mined in Korea came from mines south of latitude 38° N. Nearly 90 per cent of the output of graphite in southern Korea came from the provinces of Ch'ungch'ong-pukto and Kyongsang-pukto. Graphite ranked seventh in value among the mineral products of all Korea and fifth among the mineral products of southern Korea.

The crystalline and amorphous graphite of Korea is in rocks which range in age from pre-Cambrian to Triassic that have been subjected to contact or regional metamorphism. Workable deposits of crystalline graphite contain 3 to 4 per cent of disseminated graphite flakes generally in granitic rock that has intruded calcareous schists of sedimentary origin. Deposits of amorphous graphite are irregular lenses parallel to the structure of enclosing schists and phyllites of

[1] Published by permission of the Director, U. S. Geological Survey.

sedimentary origin. Some impure amorphous graphite has formed from beds of coal that have been subjected to dynamic and igneous metamorphism.

Few machines were used in the graphite mines of southern Korea; generally the crude ore was sorted, crushed, and washed by hand, although flotation was used in some places.

Descriptions are given of the Oryu, Sanya-Wolmyong, and Sogung graphite mines.

Large reserves of graphite remain that are potentially Korea's most readily exportable mineral commodity. But the mines have been closed since August 1945 and have not been reopened because of the unsettled political situation, poor communications, and the managerial inexperience of the Koreans. In time, Korea may once again become the world's largest producer of graphite.

PHOSPHATE DEPOSITS OF THE FORMER JAPANESE ISLANDS.[1]

JOHN RODGERS.

Fairly small phosphate deposits on several of the former Japanese islands in the Pacific produced about one-quarter of the phosphate rock used in Japan in the decade before the war. During the early part of the war, the Japanese increased production greatly and gutted most of the deposits. Later in the war, most of the mining installations were badly damaged. Only Kida-daito, which was relatively undamaged, and Angaur, which has relatively large high-grade reserves, are even marginally economic under present conditions.

Most of the deposits occur as an irregular mantle of phosphate or phosphatic clay over and between bizarre pinnacles of raised "coral" limestone. Phosphatic solutions from bird droppings attacked the limestone; further weathering and solution produced the phosphatic mantle and shaped the pinnacles. However, the best deposits on Angaur are blanket deposits under swamps and apparently represent further alteration of deposits of the first type.

[1] Published by permission of the Director, U. S. Geological Survey.

SULPHUR DEPOSITS OF JAPAN.[1]

A. H. CHIDESTER.

Sulphur is one of Japan's important and abundant natural resources. Sulphur is used in Japan in the paper pulp and rayon industries, the chemical industry, and in the manufacture of insecticides and disinfectants. Japan does not use refined sulphur in the manufacture of sulphuric acid, which is manufactured entirely from pyrite or as a by-product of metal smelting. Sulphur is an important export commodity, and Japan has for many years carried on an extensive export trade, chiefly to New Zealand, Australia, India, China, and Manchuria.

All of the sulphur in Japan is of volcanic origin; hence it is limited in distribution to areas of volcanic rocks. Deposits, varying widely in size and importance, occur from the Kuriles to Formosa. The most important sulphur-mining districts are in northern Honshu, central Honshu, southern Hokkaido, and northeastern Hokkaido.

The sulphur deposits of Japan may be divided into five genetic types: sedimentary, impregnation and replacement, complex, sublimation, and flows. *Sedimentary* deposits were formed by precipitation, in hot crater lakes, of elemental sulphur accompanied by deposition of clastic volcanic material. The deposits consist of alternating beds of sulphur-rich material and barren clastic material. *Impregnation and replacement* deposits were formed by sulphurous hot waters percolating through porous rocks. Such deposits are irregular in outline, and the sulphur is distributed more or less unevenly throughout the rock. *Complex* de-

[1] Published by permission of the Director, U. S. Geological Survey.

posits are partly of sedimentary and partly of impregnation and replacement origin. They show the features of the impregnation and replacement type superimposed upon and modifying features of the sedimentary type. *Sublimation* deposits were formed in porous, generally loose material, such as ash, by fumarolis gases which permeated the porous beds and deposited elemental sulphur in the interstices between the grains. Sulphur flows are a special type in which sulphur, concentrated by one of the mechanisms enumerated above, is brought to the surface of the earth in a molten state by a geyser-like action.

In Japan, although relatively few such deposits have as yet been recognized, the complex type deposits is most important economically, being large and relatively high grade. Impregnation and replacement deposits, although numerous, are in general of small or moderate size, and are second in importance. Sedimentary deposits and sublimation deposits are, in general, small and of minor importance. Flows are very rare, and, although of high purity, are relatively small; so they are of minor importance.

HYDROTHERMAL GYPSUM IN JAPAN.[1]

A. L. JENKE.

Gypsum mining in Japan is confined to the island of Honshu. Here it is concentrated in essentially two outstanding areas—one in southwestern Honshu and the other in the north-central part of that island. During 1940–1944 the north-central part accounted for 34 per cent for the total Japanese production whereas the southwestern area accounted for 30 per cent. The remainder came from an aggregate of scattered mines—all located in northern Honshu. No one gypsum mine in Japan is an outstanding producer.

Production increased steadily from 1925 to 1941 and thereafter declined rapidly to the present. This decline was due to cessation of critical wartime construction, stoppage of civilian construction, and loss of labor to the more critical industries and to the Army.

The quality of Japanese gypsum is low and averages about 33 per cent SO_3. It is suitable mainly for use in cement where it acts as an inhibitor, lengthening the setting time. A very small part (approximately 1 per cent) of the highest grade domestic production is utilized in the manufacture of plaster of paris.

Reserves of cement grade gypsum are believed to be adequate for many years to come but it is not likely Japan will produce sufficient gypsum of plaster grade, and imports of high quality material will have to be continued as in the past.

Gypsum deposits in Japan are apparently all hydrothermal in origin and are found almost entirely in shales or volcanic rocks such as andesite, liparite, and tuff, all Tertiary in age. The deposits are massive, lenticular in shape, and are made up of white-to-light-gray earthy, clayey, gypsitic rock cut by numerous sinuous veins of high-grade cross fiber and slip fiber crystalline gypsum. Mining for the most part is carried on by simple overhand stoping methods.

[1] Published by permission of the Director, U. S. Geological Survey.

THE YANG-CHIA-CHANG-TZU MOLYBDENITE DISTRICT, MANCHURIA.[1]

THOMAS A. HENDRICKS.

The Yang-chia-chang-tzu molybdenite district is in southwestern Laioning province, Manchuria, 35 miles west of Hulutao on Laiotung Gulf.

After an early history as a lead-zinc producer the district was revived by the Japanese in 1935. By 1939, 500 tons of lead-zinc ore were milled daily, and in 1939 molybdenite was discovered. Molybdenite ore production increased to 500 tons per day in 1944 and lead-zinc production ceased. From January, 1944, to

[1] Published by permission of the Director, U. S Geological Survey.

August, 1945, molybdenite ore production was 800 tons per day, totaling 400,000 tons averaging 0.40 per cent molybdenite.

The metalliferous deposits occur in epidotized marble in the lower half of early Paleozoic limestone about 800 meters thick in contact with Cretaceous granite. The deposits are in two sets of veins normal to the limestone bedding and in lenses parallel to the bedding. One vein 40 meters wide has been mined by open cut. No quartz, scheelite, or copper minerals are reported. The deepest shaft is 150 meters with 5 working levels with the lowest workings still in ore. The mines extend for 8 kilometers along the granite-limestone contact and the full extent of that contact has not been explored.

Japanese reserve estimates were 4,000,000 tons each of proved ore and probable ore continuing 0.40 per cent molybdenite. Estimates at higher cut-off values were unavailable but one shaft yielded ore averaging 1.0 per cent and local pockets run up to 7 per cent.

Grinding and flotation practices are standard.

RESUMÉ OF THE MINERAL INDUSTRY IN SOUTHERN KOREA.[1]

DAVID GALLAGHER.

Over 50 industrially useful metals and minerals are found in southern Korea. The area of southern Korea is only 35,000 square miles, yet within this small area there are over 1,400 mines and prospects. Although the mineral deposits of southern Korea are highly diverse in character, numerous, and widespread in occurrence, they are mostly small in size and low in grade. The Japanese prospected Korea thoroughly, and they exhausted, or seriously depleted, many of the mineral deposits. The economic status of the various mineral commodities found in southern Korea is summarized. The commodities that afford the chief hope for the future of the mineral industry in southern Korea are gold, graphite, tungsten, and bismuth.

[1] Published by permission of the Director, U. S. Geological Survey.

THE IRON AND STEEL INDUSTRY OF THE FORMER JAPANESE EMPIRE.[1]

T. Z. JOHNSTON.

Although deficient in raw materials for making iron and steel, Japan became one of the ranking steel producers of the world by building processing plants in the Home Islands and importing large quantities of coal, iron ore, scrap iron, pig iron, and semifinished steel. From a production of approximately one million metric tons of pig iron and two million tons of steel in 1931, the industry was expanded to four million tons of pig iron and eight million tons of steel in 1943, the year of peak production. After 1943 production declined and practically ceased with the end of hostilities in 1945. Since then, left-over war stocks have been utilized to produce small amounts of domestic products.

Expansion also took place in the Japanese dominated countries of Korea and Manchuria where a combined peak production in 1943 amounted to over two million tons of pig iron and nearly one million tons of steel. These two countries and North China were also sources of raw materials, especially after 1941 when the war cut off other imports.

Equipment and methods were similar to those used in other steel producing countries. Six installations of major integrated plants in Japan accounted for about 90 per cent of the production of pig iron and more than one-half of the production of steel. Many small units contributed the remainder with electric furnaces and rotary kilns playing important roles especially in alloy steels. Two plants in Korea and two in Manchuria accounted for the bulk of the production of those countries.

[1] Published by permission of the Director, U. S. Geological Survey.

THE LOW-TEMPERATURE CARBONIZATION OF COAL IN JAPAN.[1, 2]

WILLIAM T. REID.

During the war, Japan was in urgent need of liquid fuels. Being poorly supplied with petroleum, but having large deposits of coal, it was natural that methods of producing liquid fuels from coal should have been developed intensively. Most successful for this purpose was the low-temperature carbonization of coal, six plants in Japan proper and four in Karafuto and Korea, under Japanese control, producing a total of 2,610,000 bbl. of liquid fuels from 1940 until the end of the war. Although not a significant amount of fuel compared to that required for a nation at war, nevertheless it represented a production seven times greater than that obtained from synthetic processes based on coal, such as the Fischer-Tropsch and the Bergius methods.

Semi-coke produced from the low-temperature carbonization of coal also was important although it was classed as a by-product, for the primary objective of most of these plants was the production of liquid fuels. This semi-coke, a reactive, free-burning, smokeless fuel, was used for domestic heating and cooking as a substitute for charcoal, for gasification processes, as a fuel for portable gas producers used on automotive vehicles, and to replace imported low-volatile bituminous coal in the manufacture of metallurgical coke. Since 1936, one plant produced more than 300,000 tons of semi-coke for blending with bituminous coal to form coke. The total production of semi-coke in Japan since 1923 is approximately 2,000,000 tons.

Equipment used is primarily of German design. Just prior to the end of the war, 6 plants using 20 Lurgi carbonizers were operating with a total rated capacity of more than 1,500,000 tons of coal per year. At the same time, 2 continuous steaming vertical Koppers units had a combined annual capacity of 400,000 tons of coal. However, despite this high-rated capacity, the maximum amount of semi-coke produced in any one year was 468,446 tons. Japanese-designed plants, such as the Mimura, had been operated during the war, but with so much mechanical trouble because of faulty design considerations that the output from these sources was small. The Wanishi carbonizers, also of Japanese design but based on the Thyssen carbonizer developed in Germany, operated satisfactorily. Knowles ovens, exactly duplicating those in the United States, were being built at the end of the war, but only a single installation had been in operation.

No true low-temperature carbonization process used in Japan could carbonize strongly caking coals satisfactorily. The Mimura process designed for this purpose was unsuccessful, as was the earlier Shimomura process, while the Lurgi, Koppers, and Wanishi systems operated only with noncaking or very weakly caking coals. The Knowles ovens, really operating in the medium-temperature range, alone could carbonize caking coal without difficulty.

War damage to these plants was severe. Only 3 were left in operating condition or were so slightly damaged that only minor repairs would be required to put them back into operation. More than half the total capacity was in Korea and Karafuto, no longer available for Japanese operation. The future status of the remaining plants still is uncertain, depending upon economic conditions within the country as well as control by the occupation forces. With the removal of the war-induced incentive for the production of liquid fuels at any price, it appears likely that normal conditions will make the operation of such plants less attractive.

[1] For presentation at joint meeting of the Society of Economic Geology and the American Institute of Mining and Metallurgical Engineers, New York, March 20, 1947.

[2] Published by permission of the Director, U. S. Geological Survey.

STRUCTURE AND ORE DEPOSITS OF THE KIRKLAND LAKE–NORANDA–VAL D'OR BELT, ONTARIO AND QUEBEC.

The territory extending from Kirkland Lake, Ontario eastward to Louvicourt township, Quebec, includes numerous mines, some of which are among the most

important in the Canadian pre-Cambrian Shield. The production of gold, copper, zinc, and other metals from this zone since 1912 in Ontario and 1927 in Quebec has had a total value of over $1,000,000,000.

Except for some ridges of (Huronian) Cobalt series and dikes of diabase of Late pre-Cambrian age, the bedrock formations of the region belong to the Archean and have been highly folded and are traversed by numerous faults most of which are of the overthrust type. Nearly all the faults are marked by zones of schistosity and intense alteration to carbonate, chlorite and talc.

In the middle section of the zone the Archean rocks are volcanics, and clastic sediments that have been invaded by diorite, granite, and other igneous intrusives. All of the ore deposits are associated with faults or drag folds related to faults. The two most important faults are the Horne Creek and the Cadillac-Bouzan Lake. The last except for one interruption extends continuously across the region to near the Ontario boundary where it disappears beneath the Late pre-Cambrian Cobalt series. It is probably continuous with a similar fault described by Thomson in the Kirkland Lake-Larder Lake area. The ore deposits associated with the Horne Creek fault are of the copper-gold type whereas those so far discovered adjacent to the Cadillac-Bouzan Lake fault are gold-bearing only.

SCIENTIFIC NOTES AND NEWS

OLIVER BOWLES, after 33 years of Government service, has retired as chief of the nonmetal economics division of the Bureau of Mines.

C. A. HEILAND has been elected president of the Rocky Mountain Association of geologists.

JAMES A. NOBLE, Chief Geologist of the Homestake Mining Corporation, has been granted a leave by his company in order to permit him to serve as Professor of Metalliferous Geology at the California Institute of Technology starting September 1, 1947. Dr. Noble will fill the place formerly occupied by Dr. H. J. Fraser, who is now General Manager of the Falconbridge Nickel Mining Company.

The U. S. Civil Service Commission announces a written examination for geologists at salaries of $2,644.00 and $3,397.00 a year for which applications must be received by the Commission in Washington by May 8, 1947. Competitors must write a written test and completed by September 1, 1947, a bachelor's degree in geology or have had 30 semester hours in geology, and experience equivalent to a 4-year course in geology. For the higher salary applicants must have had two years' professional experience.

W. JAMES BICHAN has been retained by the New Brunswick Government to initiate an extensive program of mineral exploration, and with the aid of graduate and undergraduate assistants, will commence operations in the southern portion of the Province.

BENNETT R. BATES recently returned from Senegal, West Africa.

FELIX WORMSER will join the staff of the St. Joseph Lead Co. on May 15 as assistant to Andrew Fletcher, president of the company.

ELIS DAHLSTROM has completed over one year of his two-year contract with the Ethiopian Government as chief geologist and director of geological work. His address is Box 815, Addis Ababa, Ethiopia.

RALPH TUCK has been appointed geologist in charge of western exploration for the U. S. Smelting, Refining and Mining Co. For three years he was stationed at Fairbanks and Nome, Alaska, as geologist for the company.

PAUL C. HENSHAW resigned as acting head of the geology department at the University of Idaho School of Mines, expecting to go to work for a Mexican mining company. Mr. Henshaw had been senior geologist for the Tamarack and Custer Consolidated Mining Co. at Wallace, Idaho.

RAOUL MITCHELL, formerly of Hunter College, New York, has been named assistant professor of geology and geophysics at Tulane University, New Orleans, La.

M. I. SIGNER has been appointed dean of the faculty of the Colorado School of Mines, replacing Col. James Boyd.

D. F. HEWETT, staff geologist of the United States Geological Survey, is engaged in completing reports on areas in southeastern California. He will return to Washington about July 1.

JOHN C. DAVEY and VICTOR M. LOPEZ have been awarded the gold medal of the Venezuelan Academy of Natural Sciences "in recognition of their outstanding work in Venezuela in the field of economic geology and mining economics."

SIR JOHN SMITH FLEET, geologist and author, former director of the Geological Survey of Great Britain and of the Museum of Practical Geology, died in London on January 27 last at the age of 77.

RALPH ARNOLD, consulting geologist and engineer, announces the removal of his office to 1205 Wilson Avenue, San Marino 9, California.

The Industrial Diamond Information Bureau, originally established in 1943 by The Diamond Trading Company Limited at 32/34 Holborn Viaduct, London, E. C. 1, has been taken over by the Diamond Research Department of Industrial Distributors (1946) Ltd. (Incorporated in the Union of South Africa), and the Bureau will continue to maintain at the same address an up to date reference library on scientific and technical aspects of diamond, including patents, and to invite inquiries from users on industrial problems encountered in the industrial use of cutting tools, wire drawing dies, abrasives, and other applications of diamond. The monthly bibliography of literature dealing with matters relating to the industrial use of diamonds will continue to be published, and a free technical service to all industrial users of diamond will, where possible, continue to be offered.

ALEXANDER DEUSSEN, consulting geologist of Houston, Texas, received in Los Angeles on March 25th, at the Annual Meeting of the American Association of Petroleum Geologists, the Sidney Powers Memorial Medal Award of the American Association of Petroleum Geologists "in recognition of distinguished and outstanding contributions to, or achievements in, petroleum geology."

CLARENCE S. ROSS was awarded the 6th Roebling Medal of the Mineralogical Society of America.

HOWARD W. ADAM has been named to the staff of Battelle Memorial Institute, Columbus, Ohio, where he will be associated with its minerals research division.

J. W. AMBROSE has been elected president of the newly organized Geological Association of Canada, which followed a meeting of the Prospectors and Developers Association in Toronto. Dr. Ambrose is an alumnus of Stanford and Yale and was from 1935 to 1945 on the staff of the Geological Survey of Canada. Since 1945 he has been in private consultation work and special lecturer in geology at Queen's University, Kingston, Ont.

ROBERT P. SHARP, an alumnus of the California Institute of Technology and of Harvard, after holding the chair of assistant professor of geology at the University of Illinois for four years and then serving three years with the Arctic Section of the A. D. T. I. C. unit of the Army Air Forces, will join the faculty of the California Institute of Technology in September as professor of geomorphology. Dr. Sharp was recently professor of geomorphology at the University of Minnesota.

JOHN S. BROWN, chief geologist of the St. Joseph Lead Co. in New York City, has been transferred to Bonne Terre, Mo.

C. A. BOTSFORD, former minerals attaché of the American Embassy, Rome, who returned home late in September, has left for Tokyo, for the civil affairs division of the War Department to serve as mining engineer of the National Resources Section at General MacArthur's headquarters. Before going to Rome he was minerals attaché at Havana, having joined the State Department's Auxiliary Foreign Service in January 1942, prior to which he had been mining in Latin America since 1924.

ROSWELL W. PROUTY, when the minerals attaché office in Mexico was abolished last July, returned to the Bureau of Mines and was assigned to the Minneapolis division. Temporarily he is stationed at Rapid City, S. Dak., doing some work in the Black Hills.

J. OSBORN FULLER has joined the geology department of Ohio State University at Columbus. He had been teaching at West Virginia University, Morgantown, as assistant professor of geology.

J. P. GRIES has returned to teaching at South Dakota School of Mines, Rapid City, as associate professor of geology and is available for consulting work. He has been associated with Magnolia Petroleum Co., Midland, Texas.

JOHN R. REYNOLDS, formerly project and examining engineer with the Bureau of Mines on the Pacific Coast, has entered the consulting geological and mining engineering field with his office in the Idaho First National Bank Bldg., Kellogg, Idaho. He was at one time associated with the U. S. Geological Survey.

RAYMOND BROOKS has gone to Rhodesia in the capacity of managing director to direct mining exploration work for Rhodesia Copper Ventures, a company organized and financed with British capital in South Africa. It is intended to conduct a thorough investigation of copper and other mineral deposits in south-central Africa, giving particular attention to Southern Rhodesia. Mr. Brook's address is P. O. Sinoia, S. Rhodesia.

JAMES M. SCHOPF, paleobotanist at the Central Experiment Station of the Bureau of Mines, Pittsburgh, has been granted a leave to make a paleobotanical and petrologic study of South African coal deposits under the auspices of the South African Council of Scientific and Industrial Research at the laboratories of the South African Geological Survey in Pretoria.

OLAF P. JENKINS has been appointed chief of the division of mines, Department of Natural Resources, of the State of California. He has been with the division since 1929 as chief geologist.

R. C. ALLEN, executive vice-president of Oglebay, Norton and Co., and former vice-chairman of the WPB, has been made president of the board of trustees of Battelle Memorial Institute. A geologist, mineral economist, and iron mining company executive, Mr. Allen is president of the Lake Superior Iron Ore Association and a former director of the Michigan Geological Survey.

CHARLES P. BERKEY, professor of geology at Columbia University, celebrated his eightieth birthday at his home at Palisade, N. J., on March 25.

DR. THOMAS THORNTON READ, Vinton Professor of Mining, Emeritus, at Columbia University, died at White Plains, New York, May 29, aged 67.

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